THIS NUMBER COMPLETES VOLUME XXVII

Volume XXVII June, 1929 Number 6

SOIL SCIENCE

Contents

PUBLISHED MONTHLY
THE WILLIAMS & WILKINS COMPANY
MT. ROYAL AND GUILFORD AVENUES
Baltimore, Maryland, U. S. A.

Made in United States of America

SOIL SCIENCE

FOUNDED BY
RUTGERS COLLEGE
New Brunswick, N. J.

EDITORIAL BOARD

Entered as second-class matter May 12, 1919, at the post office at Baltimore, Maryland, under the act of March 3, 1879

ERRATA

American soils as seen by Russian investigators, by J. S. Joffe and I. Antipov-Karataev, Soil Science, Vol. XXVII

Papes 161—Second line from bottom, *240* should read *740*.

Page 162—Sixth line from bottom, *310* should read *31°*.

Microbiological activities in the soil of an upland bog in eastern North Carolina, by I. V. Shunk, Soil Science, Vol. XXVII

Pages 288 and 291, the cuts for figures 1 and 2 should be reversed, the legends being left unchanged in their present positions.

THE RELATIONSHIP OF SOIL TYPE TO THE CALCIUM AND MAGNESIUM CONTENT OF GREEN BEAN STEMS AND LEAVES AND OF THEIR EXPRESSED JUICE[1]

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Received for publication January 2, 1929

In a previous paper (9) the influence of soil type upon the calcium and magnesium content of alfalfa was discussed. Data on the relationship of soil type to the calcium and magnesium content of the bean plant are set forth in this paper.

Since beans grow readily under greenhouse conditions, thus permitting of carefully controlled experiments, it was possible not only to determine variations in the composition of the plants with respect to calcium and magnesium but also to study the relationships between certain characteristics of the soils and the calcium and magnesium content of the plants. These data are made a major part of the discussion included herein.

REVIEW OF LITERATURE

Burd (4) showed that the correlation between the amounts of plant-food in uncropped soil and the crop-producing power of the soil is sufficiently great to justify the belief that the amounts are a measure of the soil's crop-producing power. Duley (7) found no very definite correlation between the calcium in the soil solution and the soil's ability to produce crops under field condition. According to Russell (22), Brazeale's work shows that small variations in the concentration of the soil solution are without effect on the growth of plants, but Rothamsted's experiments have shown the growth of crops to vary directly with the concentration of the soil solution.

Since the addition of some fertilizers enriches the soil solution, as explained by Kelley (15), and since several workers (1, 10, 16, 17, 19) have found that the addition of fertilizers influences the composition of plants, it is possible that there is a relationship between the composition of the soil solution and the composition of plants.

Burd (4) asserts that good, uncropped soils may contain considerably more solutes than poor, uncropped soils, but both good and poor soils are reduced to the same low level by growing plants. Hoagland (13) states that from

[1] Part 2 of a thesis presented to the graduate committee of Michigan State College in partial fulfillment of the requirements for a degree of doctor of philosophy.

[2] The writer wishes to express sincere appreciation to Dr. M. M. McCool for his kindly suggestions and criticisms in the execution and presentation of this work.

neither the water extract nor the freezing point method is there any indication that the soil solution has a constant composition; on the other hand, the soil solution may vary greatly under different conditions and a growing crop markedly diminishes its concentration. The soil solution under conditions favorable to crop growth was found by Hoagland (13) to be very dilute, especially during the height of the growing season. Duley (7) found the calcium content of Colby silt loam to be reduced from 22 to 54 per cent by a crop of clover. Stewart (23) showed that soils under crop always contain smaller amounts of calcium and magnesium than their uncropped duplicates. According to Burd (5), the water extracts of soils on which barley was growing showed variations in the calcium and magnesium content which were related to the content of these in the plants; as there was an increase in the plants, there was a decrease in the water extract. McCool and Millar (18) found that the freezing point lowering of the tops of plants was not very sensitive to changes in the concentration of the soil solution.

Duley (7) concluded there was a closer correlation between the amount of calcium in a soil soluble in 0.04 normal carbonated water and the soil's response to liming than there was between the pH value of the soil and this response.

Fleetwood (8) determined that the amount of calcium soluble in 0.04 normal carbonated water in the 0-7 inch layer of soil was closely related to the returns from application of lime to the soil. Swanson, et al, (24) showed a close correlation between the calcium content of the soil soluble in cold normal hydrochloric acid and the pH value of the soil, provided the soils were all of the same texture. Duley (7) ascertained that in nearly all cases the addition of lime increased the amount of calcium in the soil solution.

Russell (23) states that soils kept in dry conditions increase the amounts of their available plant-foods. Duley (7) found that very acid Kolby silt loam increased the concentration of the calcium in its soil solution when kept in the greenhouse for a number of months.

PLAN OF THE EXPERIMENT

Although primarily intended to show variations which may occur in the calcium and magnesium contents of green bean stems and leaves and in their expressed juice at different stages of growth, when the bean plants are grown on different soil types, the work presented here was planned also to show the effect of crop growth upon the concentration of calcium and magnesium in the soil solution and upon the pH value of the soil and the relationship of these to the composition of the plants. The textures of the soils in relation to the calcium and magnesium contents of the plants were also observed.

The experimental work consisted of growing Robust field beans in 2-gallon crocks containing surface soils of seven different types. Five pots of each soil type were planted with beans. One pot of each soil type was planted to grow 20 bean plants for the first sampling and the remaining four pots to carry 7 plants for the subsequent samplings.

The soil types used in this experiment included Roselawn loamy sand, Plainfield loamy sand, Kewanee sandy loam, Onaway sandy loam (heavy phase), Hillsdale sandy loam, Brookston loam (heavy), and Miami silt loam. The Roselawn was much more alkaline than is typical and the Plainfield had been limed. The Miami was very heavy and appeared to include at least some subsoil material. From the textural standpoint, the soils fell into two distinct groups, the one very light and including the sandy soils, and the other very heavy, consisting of the Brookston and Miami soils.

The analysis was planned to show the amounts of calcium and magnesium present in both the leaves and the stems and likewise in the expressed juice of each of these. The green weights of the stems and leaves were also obtained. The hydrogen-ion concentration of the soils and the amounts of calcium and magnesium present in the soil solutions were determined at each sampling. The soil solution consisted of the displaced liquid portion of the soil.

EXPERIMENTAL PROCEDURE

The experiments were begun in the greenhouse on February 2, 1928, when 35 two-gallon pots were planted to Robust field beans.

The first samples were taken on February 21, as soon as the plants were large enough to furnish enough material for analysis and the second when the plants were 6 weeks old. The third samples were obtained when flower buds had appeared, regardless of the age of the plants; the fourth, when the fruit was setting; and the fifth, when the pods were well filled out but the plant material had not started to wilt. All samples were taken between 8 and 10 a.m. and only on clear days, in order to reduce to the minimum variations due to shading and intensity of transpiration. As the plants were cut from each pot, the leaves and stems were separated, weighed immediately, and placed in a saturated atmosphere to prevent loss of moisture.

In the laboratory the plant parts were cut into very small pieces to allow a more representative sample to be taken. In most of the work, two or three grams of the green material was weighed out for total analysis and the juice extracted from the remainder.

The juice of the green material was obtained by the pressure method described by McCool and Weldon, (19) and at seven tons pressure per square inch. This great pressure was necessary because of the small amount of material available. The expressed juice thus obtained was not centrifuged but was weighed directly into crucibles and ashed along with the green material in a muffle furnace at dull red heat. Especially in the early stages of growth and with the expressed juice, the amount of each sample was so small that some method was required which would give the maximum amount of material for each determination. Therefore, the ashed material was taken up in 5 normal hydrochloric acid and made up to 110 cc. Of this solution, 50-cc. aliquots were used for each determination, allowing that five-elevenths of all the material be done in duplication.

The calcium determinations were made by the official volumetric method and the magnesium by the volumetric method of Handy (11). Twentieth normal $KMmO_4$ and KOH standard solutions respectively were used in each determination and the averages of only closely agreeing duplicates are reported here.

Immediately following the removal of the plants from the pots in the greenhouse, the soil was carefully sieved and portions were taken for the determination of the moisture content, the hydrogen-ion concentration, and the soil solution respectively.

The moisture content of the soil was based upon the weight of the absolutely dry soil obtained by heating in an electric oven at 105°C. for 15 hours.

The hydrogen-ion concentration was determined by the quinhydrone method of Briilman as described by Baver (2).

The suggestions as to technique made by Briilman and Tovborg-Jenson (3) and by Baver (2) were observed.

The soil solutions were obtained by the modified Lipman's direct water pressure method described by Burd and Martin (6) and supported by a number of workers, including Parker (2), Parker and Tidmore (21), and Hubbard (12). One thousand grams of soil was packed into the tubes, covered with 200 cc. of water and the soil solution displaced under pressure, which ranged from 40 to 50 pounds per square inch. The first 10 cc. of soil solution were discarded and the next 30 cc. caught and analyzed by the same method as was used for the first material. The distilled water used for watering the plants and for analytical purposes was obtained by distilling tap water through block tin pipes.

EXPERIMENTAL RESULTS

The data obtained from this experiment consist of those bearing upon the variations in the calcium and magnesium content of the bean plants at different growth stages when grown on different soil types, which show also the relationship of these variations to certain properties of the soils, and also of those related to the influence of the growth of the plants upon certain properties of the soils. Since a knowledge of the latter data is necessary to an understanding of the former, the latter are considered first in the following discussion.

Effect of the growth of beans upon certain characteristics of the soil, and the variations of different soil types in this regard

The marked influence of the growth of beans on the soil solution is shown in tables 1 and 2, where the calcium and magnesium contents, respectively, are given for the growing period of the plants.

Great differences were found to exist in the amounts of calcium present in the various soil solutions before plant growth started. The solutions of Roselawn loamy sand contained more than six times as much calcium as did the solution of Plainfield loamy sand, with the other soils solutions varying in between.

During the growth of the plant the calcium content of the soil solutions was reduced to a low level in which there was little variation. Usually the solutions of the soils which were highest in the beginning remained highest during the growth period.

Smaller amounts of magnesium than of calcium were present in the soil solutions. Although the range of difference in the soil types was small, it is evident that the soil solutions varied in the amounts of magnesium they

TABLE 1

Variations in the calcium content of soil solutions growing beans

Parts per million of water-free soil

SOIL TYPE	INITIAL Ca CONTENT	STAGES OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
Plainfield	10.60	12.50	2.68	2.16	5.05	4.00
Kewanee	44.70	24.60	30.40	......	16.10	....
Onaway	24.55	9.71	12.85	.....	.....	3.33
Roselawn	66.80	36.00	37.00	27.80	.....	8.95
Hillsdale	14.62	16.65	31.30	23.00	17.80	3.18
Brookston	19.10	.....	13.05	6.90	.....	3.33
Miami	30.06	26.90	26.62	.....	.....	6.89

TABLE 2

Variations in the magnesium content of soil solutions growing beans

(Parts per million of water-free soil)

SOIL TYPE	INITIAL CONTENT	STAGES OF GROWTH OF BEANS			
		3 weeks	6 weeks	Budding	Fruiting
Plainfield	4.44	3.089	Trace	Trace	0.7488
Kewanee	8.88	3.390	4.086	....	2.784
Onaway	7.45	2.056	1.938	....	Trace
Roselawn	9.84	3.900	3.354	....	1.114
Hillsdale	4.08	2.394	6.384	....	5.548
Brookston	3.48	0.926	1.566	....	1.600
Miami	10.20	5.810	5.352	....	....

contained; the soil solutions which were high in calcium generally were likewise high in magnesium.

No relationship appeared to exist between soil texture and the calcium or magnesium content of the soil solutions. The very sandy soils had either very high or very low calcium and magnesium contents in their solutions and the same was true of the fine textured soils.

The hydrogen-ion concentrations of the soils used are given in table 3, where it may be seen that a wide range of reaction existed, Miami soil being the most acid, with a pH value of 5.0 and Roselawn the most alkaline, with a pH

value of 7.8. No appreciable change occurred in the pH value of the soils during the growth period of the plants. The fluctuations appear to have been within the range of the influence of moisture and temperature changes and of biological activities.

Apparently there was no relationship between the pH values of the soils and the amounts of calcium and magnesium in the soil solutions.

Since it developed that the solutions of the soil types used varied in calcium and magnesium, in the order of Roselawn loamy sand, Kewanee sandy loam, Onaway sandy loam, Hillsdale sandy loam, and Plainfield loamy sand for the coarse-textured soils, and of Miami silt loam and Brookston loam for the fine-textured soils, and since the soil types fell into about this same order in respect to the extent that the calcium and magnesium contents of their solutions were maintained during the growth period, throughout the following work the soils will be considered as of decreasing strengths in this same sequence.

TABLE 3

Changes in pH values of soils growing beans

SOIL TYPE	INITIAL VALUE	STAGES OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	pH	*pH*	*pH*	*pH*	*pH*	*pH*
Plainfield	7.35	7.40	7.30	7.17	7.30	7.25
Kewanee	5.10	5.18	5.20	....	5.12	....
Onaway	7.40	7.27	7.36	....	7.37	7.42
Roselawn	7.85	7.87	7.87	7.72	8.00	7.80
Hillsdale	6.25	6.39	6.20	6.37	6.10	6.72
Brookston	7.05	6.94	7.08	6.66	6.75	....
Miami	5.00	5.10	4.60	....	....	5.64

Calcium content of green bean stems and leaves at different growth stages

The calcium content of green bean stems varied on the different soil types throughout the growth period, as is shown in table 4, where the soils are separated into light and heavy groups and then arranged according to decreasing amounts of calcium in their solutions at the beginning of the growth period. It is evident that the higher calcium contents occurred in green bean stems grown on soils with the greater amounts of calcium in their solutions. Some deviations from this appeared but the general tendency was very marked in this regard.

Considering that the calcium content of green bean stems was highest on Roselawn loamy sand and lowest on Plainfield loamy sand during the entire growth period, and that the stems grown on the very heavy soils contained about the same amount of calcium as stems grown on some of the very light soils, it appears that there was no relationship between soil texture and the amount of calcium in the green bean stems.

Similarly, the hydrogen-ion concentration appears to have borne no direct relationship to the amount of calcium in the green bean stems. Although the pH value of the Roselawn soil was highest and the calcium content of stems grown upon it was likewise highest, the pH value of the Plainfield soil was nearly as high, and yet the calcium content of stems grown upon this soil was lowest; Miami silt loam and Kewanee sandy loam had very low pH values and stems grown upon them had calcium contents about equal to the stems grown on soils with higher pH values, as Onaway sandy loam and Hillsdale sandy loam.

Larger percentages of calcium were present in the mature green bean stems than when the stems were young. The increase from early growth to maturity was not uniform and there generally appeared on each type an intermediate period during which little calcium was added to the stems, or during which calcium was actually removed. A large increase of calcium occurred in the stems grown on all soil types for which data were obtained except Brookston clay loam after the fruit had set.

TABLE 4

The effect of soil type on the calcium content of green bean stems at different stages of growth

SOIL TYPE	INITIAL Ca CONTENT OF SOIL SOLUTION	STAGES OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	66.8	0.253	0.4060	0.337	0.380	0.482
Kewanee	44.7	0.187	0.255	.....	0.351	.....
Onaway	24.5	0.202	0.230	.....	0.293	0.399
Hillsdale	14.6	0.243	0.225	0.267	0.263	0.422
Plainfield	10.6	0.162	0.220	0.216	0.234	0.336
Heavy soils						
Miami	30.0	0.207	0.200	.....	.....	0.434
Brookston	19.1	0.197	0.300	0.305	0.344	0.319

In table 5 are given the amounts of calcium present in the green material of bean leaves grown on different soil types. In this table the soils are arranged as in table 4.

The calcium content was much greater in green bean leaves grown on some soil types than in those grown on others. Here again, Roselawn soil generally gave leaves with the highest calcium content and Plainfield soil gave leaves with the lowest, and throughout the period of growth, a marked relationship was evident between the calcium content of the soil solution and that of the plant material. At each stage of growth, the calcium content of the green leaves grown on the different soil types, with few exceptions, varied directly as the decreasing amounts of calcium present in the initial soil solutions.

The calcium content of bean leaves was usually high on the soil types which gave stems with a high calcium content. Because of this, it is evident that there was no correlation between the texture or the pH values of the soils and the calcium content of bean leaves grown upon them.

A marked increase occurred in the calcium content of green bean leaves as the growth period advanced. The greatest increase in calcium occurred when the leaves were between three and six weeks old and between the time the fruit set and maturity. During the intermediate period, the increase in calcium was very slow or the calcium was even depressed. Much greater amounts of calcium were present in the green material of bean leaves than in that of bean stems throughout the growth period. A more rapid increase took place in the calcium content of the leaves than occurred in the stems, resulting in a wider difference between the calcium contents of the two plant parts at maturity.

TABLE 5

Effect of soil type upon calcium content of green bean leaves at different stages of growth

SOIL TYPE	INITIAL Ca CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	66.80	0.316	0.620	0.620	0.586	0.706
Kewanee	44.70	0.361	0.530	.....	0.566	.....
Onaway	24.55	0.360	0.538	.....	0.586	0.731
Hillsdale	14.62	0.266	0.503	0.483	0.421	0.722
Plainfield	10.60	0.249	0.434	0.403	0.411	0.564
Heavy soils						
Miami	30.06	0.448	0.658	0.400	.....	0.686
Brookston	19.10	0.301	0.476	0.450	0.556	0.601

Calcium content of the expressed juice of bean stems and leaves

Variations in the calcium content of the expressed juice of bean stems grown on different soil types are shown in table 6. Very similar differences can be seen in the calcium content of the expressed juice of bean stems as was evident in that of the green material. Generally the concentration of calcium in the juice was high in the stems which contained large amounts of calcium in their green tissue. Thus it follows that a high calcium content in the expressed juice of the bean stems was associated with a high calcium content in the soil solution. Deviations from this appeared on some of the soils at various times during the period of plant growth but still the correlation between the concentration of the calcium in the soil solution and the concentration of calcium in the expressed juice of the stems was plainly very high.

No closer relationship was evident between the texture nor the pH value of

the soil and the calcium content of the expressed juice of bean stems than was evident between these and the calcium content of the green material.

In table 7 is given the calcium content of the expressed juice of bean leaves at different stages of growth and on different soil types. Wide variations occurred in the calcium content of the juice of leaves grown on the different

TABLE 6

Effect of soil type upon the calcium content of the expressed juice of bean stems at different stages of growth

SOIL TYPE	INITIAL Ca CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	66.80	0.213	0.217	0232	0.240	0.288
Kewanee	44.70	0.200	0.205	.....	0.217	.....
Onaway	24.55	0.205	0.191	0.235	0.238	.....
Hillsdale	14.62	0.138	0.172	0.191	0.178	0.206
Plainfield	10.60	0.199	0.155	0.138	0.229	0.137
Heavy soils						
Miami	30.06	0.181	0.157	.....	.....	.....
Brookston	19.10	0.127	.....	0.170	.....	0.276

TABLE 7

Effect of soil type upon the calcium content of the expressed juice of bean leaves at different stages of growth

SOIL TYPE	INITIAL Ca CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OE BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	66.8	0.365	0.529	0.583	0.595	0.635
Kewanee	44.70	0.334	.....	.....	0.599	.....
Onaway	24.55	0.271	0.595	.....	0.598	0.690
Hillsdale	14.62	0.220	0.451	0.433	0.409	0.537
Plainfield	10.60	0.167	0.326	0.313	0.338	0.515
Heavy soils						
Miami	30.60	0.368	0.555	.....	.....	0.558
Brookston	19.10	0.189	0.348	0.413	.....	0.531

soil types throughout the period of growth. The relationship of the concentration of calcium in the soil solution to that of the expressed juice was less evident here than in the cases heretofore observed, although it still appears that the concentration of calcium in the plant juice was high where the concentration of calcium in the soil solution was high. The calcium contents of

the expressed juice of the leaves grown on Roselawn, Kewanee, and Onaway soils were very nearly equal regardless of marked differences in the amounts of calcium in the soil solutions.

Since there were marked similarities in the calcium contents of the juice of leaves grown on several of the soil types differing widely in texture and in hydrogen-ion concentration, it appears that there was no relationship between either the pH value or the texture of the soils and the calcium content of the juice of the bean leaves grown upon them.

In the juice of both stems and leaves there was an increase in the calcium content as the plants became more mature. The increase was more uniform in the juice of leaves than in that of the stems and it was much more rapid, so that in the mature stage there was a wide difference in the concentration of calcium in the juice of the two plant parts, there being more than twice as much in the juice of the leaves as in that of the stems.

TABLE 8

Effect of soil type upon the magnesium content of green bean stems at different stages of growth

SOIL TYPE	INITIAL Mg CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	9.84	0.044	0.029	0.052	0.083	0.0700
Kewanee	8.88	0.054	0.016	.....	0.026	......
Onaway	7.45	0.037	0.072	.....	0.079	0.0570
Plainfield	4.44	0.034	0.056	0.066	0.048	0.0792
Hillsdale	4.08	0.042	0.016	0.061	0.052	0.0570
Heavy soils						
Miami	10.20	0.058	0.064	.....	.....	0.0260
Brookston	3.48	0.062	0.061	0.100	0.086	0.0260

Magnesium content of green bean stems and leaves

The influence of soil types on the magnesium contents of green bean stems at different growth stages, is given in table 8, where the soil types are divided into light and heavy soils and then grouped according to decreasing amounts of magnesium in their solutions.

The magnesium content of green bean stems fluctuated greatly during the growing period on each of the soil types. Although noticeable differences occurred in the amounts of magnesium present in the green material at each stage of growth on the different soil types, there evidently was no relationship between the magnesium content and either the amount of magnesium present in the soil solution or the pH value of the soils as described earlier. However, it does appear that the magnesium content was higher in the stems of plants grown on the two heavy soil types than in those of the plants grown on the

light soil types. This last relationship did not hold when the plants had reached maturity.

On the light soil types there was more magnesium present in the green bean stems when the plants had reached maturity than when they were young, but during the intermediate growth stages a high point was always reached in which the magnesium content was greater than in the mature stage. On the heavy soil types the magnesium content of the stems was always lower at maturity then in the early stages of growth.

Much less magnesium than calcium was present in the green material of bean stems throughout the period of growth and the amount present fluctuated much more than the calcium.

A somewhat more uniform amount of magnesium was present in the green material of bean leaves than in that of the stems, as is evident in table 9.

TABLE 9

Effect of soil type upon the magnesium content of green bean leaves at different stages of growth

SOIL TYPE	INITIAL Mg CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	9.84	0.058	0.077	0.096	0.193	0.114
Kewanee	8.88	0.060	0.066	.....	0.075	.....
Onaway	7.45	0.068	0.077	.....	0.083	0.140
Plainfield	4.44	0.079	0.118	0.096	0.079	0.083
Hillsdale	4.08	0.055	0.105	0.083	0.075	0.105
Heavy soils						
Miami	10.02	0.082	0.099	.....	.....	0.079
Brookston	3.48	0.060	0.105	0.123	0.092	0.123

Greater amounts of magnesium were present at each stage of growth in the green material of leaves grown on some soil types than on others. Generally, in the early growth stages at least, there was more magnesium present in the leaves grown on soils with lower magnesium contents in their solutions. This was especially noticeable on the two heavy soils though this difference here might have been due to the low pH value of the Miami soil, a possibility which is supported by the fact that the plants grown on Kewanee soil also gave leaves with a low magnesium content. Further than this, no relationship appeared to exist between the characteristics of the soils and the magnesium content of the bean leaves.

Greater amounts of magnesium were present in the green bean leaves at maturity than when they were 3 weeks old in all plants except those grown on Miami soil. The increase of magnesium from early growth to maturity was generally not uniform. More magnesium was present in the leaves than

in the stems at all stages of growth and the rate of increase was somewhat faster. Much less magnesium than calcium was present in the leaves of beans throughout the growth period.

Magnesium content of the expressed juice of bean stems and leaves

In tables 10 and 11 are given the percentages of magnesium present in the expressed juice of bean stems and leaves at different stages of growth and on different soil types. Great fluctuation in the magnesium content was characteristic of the juice of both the stems and leaves of plants grown on different soil types and it appears that soil texture, the pH value of the soil, and the concentration of magnesium in the soil solution had no controlling influence on the concentration of magnesium in the plant juice.

TABLE 10

Effect of soil type upon the magnesium content of the expressed juice of bean stems at different stages of growth

SOIL TYPE	INITIAL Mg CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	9.84	0.041	0.031	0.067	.....	0.105
Kewanee	8.88	0.053	0.036	.....	0.048	.....
Onaway	7.45	0.043	0.035	.....	.....	0.115
Plainfield	4.44	0.037	0.055	0.050	0.099	0.155
Hillsdale	4.08	0.045	0.050	0.064	0.040	0.076
Heavy soils						
Miami	10.20	0.046	0.066	.....	.....	.....
Brookston	3.48	.....	.....	0.087	.....	0.060

Greater concentrations of magnesium were usually present in the juice of both stems and leaves as the plants advanced in age. On many of the soil types this increase of concentration of magnesium in the juice was quite uniform and it also was of considerable magnitude.

Magnesium was about equally concentrated in the juice of the stems and leaves throughout the growth period. This is in contrast with the concentration of calcium in the two plant parts, which was greater in the juice of the leaves than in that of the stems and which also increased much more rapidly in the juice of the leaves.

Total green plant material produced on the different soil types

The green plant material produced on each soil type at the various periods of growth is given in grams in table 12 and the corresponding proportion of stems and leaves in per cent is given in table 13.

TABLE 11

Effect of soil type upon the magnesium content of the expressed juice of bean leaves at different stages of growth

SOIL TYPE	INITIAL Mg CONTENT OF SOIL SOLUTION	STAGE OF GROWTH OF BEANS				
		3 weeks	6 weeks	Budding	Fruiting	Maturity
	p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Roselawn	9.84	0.037	0.070	0.073	.....	0.098
Kewanee	8.88	0.024	.....	.....	0.031	.....
Onaway	7.45	0.057	0.088	.....	.....	0.109
Plainfield	4.44	0.052	0.061	0.091	0.076	0.042
Hillsdale	4.08	0.052	0.084	0.086	.....	0.088
Heavy soils						
Miami	10.20	0.057	0.122	.....	.....	0.075
Brookston	3.48	0.023	0.071	0.103	.....	0.105

TABLE 12

Green weight of beans at different stages of growth on different soil types

(Weight of 7 plants in grams)

SOIL TYPE	STAGE OF GROWTH OF BEANS				
	3 weeks	6 weeks	Budding	Fruiting	Maturity
Plainfield	9.94	32.5	33.25	42.0	40.0
Kewanee	10.20	16.0	.....	38.0	....
Onaway	10.50	19.8	.....	38.0	38.0
Roselawn	9.80	16.1	41.00	43.0	56.0
Hillsdale	12.88	26.0	45.50	46.5	55.0
Brookston	11.20	19.5	29.00	31.0	22.5
Miami	10.29	16.5	.....	....	23.5

TABLE 13

Proportions of leaves and stems of beans at different stages of growth on different soil types

SOIL TYPE	STATE OF GROWTH OF BEANS									
	3 weeks		6 weeks		Budding		Fruiting		Maturity	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	47.3	52.7	38.4	61.6	39.8	60.2	30.8	69.2	32.1	67.9
Kewanee	....	....	34.4	65.6	....	....	34.2	65.7	....	....
Onaway	45.0	55.0	35.8	64.2	....	....	36.0	64.0	31.6	68.4
Roselawn	43.0	57.0	33.0	67.0	35.3	64.7	36.0	64.0	28.5	71.5
Hillsdale	43.8	56.2	55.4	44.6	38.5	61.5	37.9	62.1	31.8	68.2
Brookston	47.7	52.3	35.8	64.2	34.5	65.5	32.2	67.9	35.5	64.5
Miami	47.4	52.6	39.3	60.7	....	....	....	....	36.1	63.9

Considerably better growth was made on some of the soil types than on others. The growth was usually light on the very heavy soils and also on the very acid soils and apparently was independent of the amount of calcium and magnesium present in the soil solutions. There is no evidence that there was any relationship between the rate of growth and the calcium or magnesium content of the plant material.

Proportion of stems and leaves of the bean plant

Some variance occurred in the proportions of stems and leaves produced on the different soil types at each stage of growth but it was small and does not appear to depend on the rate of growth nor upon the characteristics of the soil which are considered here. The proportion of stems is less than that of leaves during the entire period of growth. At the beginning of growth, the difference in the proportions was small, averaging 45.7 per cent stems and 54.3 per cent leaves. The proportion of leaves increased as the growth period advanced, with the result that at maturity the proportions were 32.6 per cent of stems and 67.4 per cent of leaves.

A comparison of calcium and magnesium contents of cropped and uncropped soils

Depressions in the amount of calcium and magnesium in the soil solutions, as was observed in this work, may not have been entirely due to the growth of the crop. To check this point, two series of pots containing Plainfield and Hillsdale soils were left fallow and sampled at the same time that two other series, containing the same soils, but growing beans, were analyzed. The results obtained are given in table 14. Here it will be seen that there were fluctuations in the amounts of calcium and magnesium present in the soil solutions of both the cropped and uncropped soils, but the general tendency was for the concentration of the elements in the solutions to decrease on the cropped soils and to hold about constant on the uncropped soils.

Power of soils to rebuild their solutions when air-dry

The noticeable reduction in the concentration of the soil solution due to the growth of plants (9, 23) indicates that during a period of rest soils must be able to rebuild their solutions in order for plant growth to be possible year after year. In the work presented here, two soils previously depleted in the greenhouse, were allowed to rest for 82 days and their solutions obtained and analyzed. The data obtained are given in table 15 where it will be seen that in the case of calcium, both Plainfield and Hillsdale soils were able to rebuild their solutions above what they were before crop growth started. These soils were held as air-dry under greenhouse conditions.

The magnesium content of the soil solutions was likewise rebuilt during the period of rest and attained a level higher than that possessed before the beginning of plant growth. Since the calcium content is reduced on Hillsdale to a lower level that on Plainfield, by the growing crop and yet after the rest

period has rebuilt its solution to contain more than three times as much calcium, it would appear that Hillsdale has more ability to rebuild its solution than has Plainfield.

Although this result is in agreement with that of Duley (7), this increase of solutes in the soil solution might perhaps be attributed to the wetting and drying of the soil. It is a question as to whether a soil maintained in the dry condition can actually increase the amount of solutes available for solution. Unfortunately this question did not present itself until too late to obtain data bearing upon it.

TABLE 14

Calcium and magnesium content of cropped and uncropped soils

Parts per million of moisture-free soil

SOIL TYPE	CALCIUM				MAGNESIUM			
	Initial content	Stage of growth			Initial content	Stage of growth		
		10 days	24 days	35 days		10 days	24 days	35 days
Plainfield cropped	17.87	8.51	1.44	1.74	6.67	2.12	9.16	1.46
Plainfield uncropped	17.81	11.91	16.30	11.15	6.67	4.99	1.57	8.73
Hillsdale cropped	38.15	32.80	12.86	4.04	12.02	11.50	1.22	0.80
Hillsdale uncropped	38.15	45.80	39.90	50.30	12.02	11.34	9.57	9.62

TABLE 15

Power of soils to rebuild their solution when dry

SOIL TYPE	CALCIUM			MAGNESIUM		
	At start of growth period	At end of growth period	After resting 82 days	At start of growth period	At end of growth period	After resting 82 days
	p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Plainfield	10.60	4.00	11.58	4.44	0.7488	6.783
Hillsdale	14.62	3.18	35.48	4.08	1.7100	10.996

SUMMARY AND CONCLUSIONS

In this work the effect of crop growth upon the calcium and magnesium content of the soil solutions and upon the pH value of the soils was observed, as were also the relationships between these characteristics of the soils and the calcium and magnesium content of the plants. Variations occurring in the calcium and magnesium contents of green bean stems and leaves and in their expressed juice when obtained from plants of different ages grown on a number of soil types were studied. The relationship of soil texture to the foregoing characteristics of the plants was noted.

Widely different amounts of calcium and magnesium were found present in the various soil solutions before plant growth began but they were greatly reduced by the growing plants and were almost equal at the end of the growth

period. The soil solutions with the highest concentrations of calcium and magnesium at the beginning of the growth period generally maintained a higher concentration during the growing period.

Insignificant variations appeared in the pH values of the different soils as the growth period advanced but they did not appear to result from the growth of the plants.

No relationship appeared to exist between the calcium and magnesium content of the soil solutions and either the pH value or the texture of the soils.

Marked variations were found in the amounts of calcium and magnesium present in the green tissue and in the juice of both stems and leaves of bean plants grown on the different soil types.

An increase generally occurred in the calcium and magnesium contents of the tissue and of the juice of stems and leaves as the growth period advanced. Some minor exceptions occurred.

The calcium content was always greater than the magnesium content. The calcium and magnesium contents of the leaf tissue were always greater than those of the stem tissue. The calcium content of the juice of leaves was always greater than that of the juice of stems but the magnesium content of the juice was sometimes greater in the stems and sometimes greater in the leaves.

Greater increases in the calcium and magnesium contents of the tissue and juice of stems and leaves generally occurred in early growth and near maturity than during the intermediate stages of growth.

A very decided correlation appeared to exist between the calcium content of the tissue and juice of both stems and leaves and that of the soil solution. A high calcium content in the soil solution was associated with a high calcium content in the plants when the soils were of similar texture.

No correlation appeared to exist between the calcium content of the plants as studied and either the texture or the pH value of the soil.

The variations in the magnesium content of the plants were so inconsistent that no correlations could be drawn between them and the magnesium content of the soil solutions, the textures of the soils, or their pH values.

There appeared to be no relationship between the rate of growth and either the calcium or the magnesium content of the plants.

There were slight variations in the proportions of stems and leaves on different soil types and they did not appear to depend on any of the properties of the soils studied. The proportion of leaves was always greater than that of stems and the ratio became wider as the period of growth advanced.

The calcium and magnesium in the soil solutions were greatly reduced in the soils growing plants, as compared with the solutions of the uncropped duplicate soils.

Plainfield and Hillsdale soils were able greatly to rebuild the calcium and magnesium contents of their solutions when kept air-dry in the greenhouse for 82 days. The Hillsdale soil surpassed the Plainfield in this respect.

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SOME INFLUENCES OF THE DEVELOPMENT OF HIGHER PLANTS UPON THE MICROÖRGANISMS IN THE SOIL: III. INFLUENCE OF THE STAGE OF PLANT GROWTH UPON SOME ACTIVITIES OF THE ORGANISMS

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Received for publication January 30, 1929

Previous reports (6, 7) have shown that the members of the soil population are greatly affected by the development of higher plants. Although all plants may affect certain of the organisms, different plants behave differently and the effects of any one plant vary with the stage of growth.

It seems likely that certain of the activities of the organisms in the soil should be affected in a manner similar to numbers of the cells since the detection of modifications in the soil population suggests that there are modifications in the transformation of such soil constituents as are associated with the nutrition of this population.

Stoklasa's results (8) showed quite clearly that, at a certain arbitrary period of measurement, the evolution of carbon dioxide from soils supporting different plants was different. It appears logical to question whether similar relationships would exist at all periods of plant growth, particularly where both annuals and biennials are involved.

It is quite natural to expect that greater amounts of carbon dioxide would be evolved from plants as they become larger (5). However, it may not be accurate to assume that the increase in carbon dioxide in the soil, a change associated with plant growth, is entirely due to excretion of carbon dioxide from the roots. Soil microörganisms may be more concerned with this change than was assumed by Barakov (1) and Turpin (9) and at least some of the increase in bicarbonates about plant roots (4) may arise from microbial activity in the rhizosphere.

Lyon and Bizzell (3) demonstrated that nitrification proceeded at different rates in soils during different periods of growth of higher plants. During the early stages of plant growth when the crops were making their greatest drafts upon the nitrogen in the soil, nitrification was most rapid and even proceeded with greater rapidity than in fallow soil at these periods. The most marked acceleration appeared under legumes. This suggests that there may be some differences in the influences of the plants upon soil activities at different periods of plant development.

The following studies are concerned with the influences which higher plants exert upon the rate of decomposition of soil organic matter as measured by the

evolution of carbon dioxide from the soil and upon the reactions concerned with the formation of nitrates in the soil.

EXPERIMENTAL PROCEDURE

These experiments were conducted simultaneously with the studies on abundance of microörganisms under higher plants as outlines in the preceding report of this series (7). Observations were made upon soils supporting growth of plants both in the greenhouse and in the field. Soils which supported no higher plants were periodically compared with soils which were gathered from plant roots.

In determining the evolution of carbon dioxide, duplicate samples of the moist soils, which were equivalent to 100 gm. of oven-dry soil, were placed in containers, brought to the same moisture content and introduced into an apparatus (11) for determining the amount of carbon dioxide which was generated in a period of 15 days at a temperature of 27°C. Only averages of the results upon the duplicate samples of soil are reported.

Nitrification studies were made only upon the field soils. They were made in two of the ways suggested by Waksman (10). In one case, samples of the moist soils, equivalent to 100 gm. of oven-dry soil, were placed in tumblers, brought to the same moisture content, covered, and incubated at 27 °C. Occasionally water was added to the soils to bring the moisture content to its original condition. At intervals varying from 5 to 30 days, determinations were made for ammoniacal and nitrate nitrogen. In the second case, nitrification of added ammonium sulfate was determined. To samples of the moist soils equivalent to 100 gm. of oven-dry soil, 210 mgm. of calcium carbonate were added and uniformly distributed throughout the soil. Some ammonium sulfate was dissolved in distilled water and an amount of the solution containing 30 mgm. of nitrogen was sprinkled over the soil and carefully mixed into it. These soils were incubated at 27°C. and periodically studied for the presence of ammonical and nitrate nitrogen.

The determinations for ammonia were made according to a method of Bengtsson (2). Extracts of the soil which were made with normal potassium chloride were distilled in the presence of magnesium oxide into standard acid which was titrated back with standard alkali. Nitrate determinations were made by the phenoldisulfonic acid method.

EXPERIMENTAL RESULTS

Evolution of carbon dioxide

Among the activities associated with microbial development, the production of carbon dioxide is one of the few which is common to practically all organisms and lends itself readily to measurement in soils. Under aerobic conditions, in a mixed population, it is the principal carbonaceous end product of decomposition. Results of determinations for the carbon dioxide which is

liberated from soils may be interpreted as indicating fairly accurately the speeds of decomposition of the organic materials in the soils. The method is much more accurate for estimating some of the influences of plant development upon the soil organisms than counts of the abundance of organisms by the plate method. Consequently, small differences in the amounts of carbon dioxide formed from the various soils may be considered as being significant where similar differences in the determined abundance of microörganisms would be within the error of the determination.

TABLE 1

*Carbon dioxide evolved from fallow soils and from soils obtained from the roots of various plants**

PLANT	AGE OF PLANT DEVELOPMENT					AVERAGE OF ALL PERIODS
	44 days	63 days	86 days	138 days	173 days	
Field soils						
Fallow	27.7	18.4	16.2	15.7	15.0	18.6
Oats	22.9	26.5	22.4	17.0	17.2	21.2
Corn	28.4	27.3	23.9	22.4	18.9	24.2
Beans	28.7	24.1	19.0	20.2	19.3	22.3
Potatoes	23.1	23.0	18.8	18.7	15.7	19.9
Table beets	21.1	23.0	20.5	20.1	28.0	22.5
Mangel beets	26.2	27.1	21.1	23.0	24.7	24.4
Rape	26.0	28.4	24.2	24.5	28.0	26.2
Sweet clover†	22.8	20.2	17.1	18.5	29.5	21.6

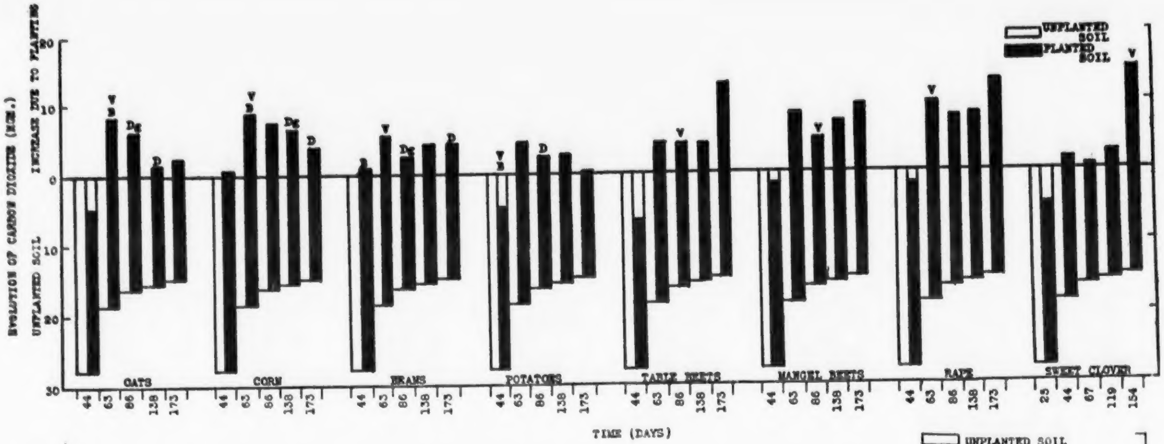
Greenhouse soils

PLANT	AGE OF PLANT DEVELOPMENT						AVERAGE OF ALL PERIODS
	36 days	59 days	93 days	128 days	169 days	202 days	
Fallow	10.3	8.7	10.8	9.6	8.2	10.6	9.7
Oats	12.8	10.1	12.6	16.9	15.2	14.8	13.7
Beans	10.5	12.1	11.0	10.9	10.2	11.3	11.0
Beets	10.7	10.4	10.6	13.9	13.7	11.7	11.8
Rape	11.2	11.0	12.2	15.6	11.9	13.4	12.6
Sweet clover	10.4	13.1	11.7	11.8	11.6	11.1	11.6

* Mgm. of carbon evolved as carbon dioxide from the equivalent of 100 gm. of dry soil in 15 days.

† For sweet clover the sampling periods are 25, 44, 67, 119 and 154 days.

Averages of the results of these studies are presented in table 1 and figure 1. Only the results of the field studies are presented graphically. From the arrangement of the data on the graph, the degree of the extension of the shaded columns above the zero line indicates the amounts of increases in evolution of carbon dioxide due to plant growth. The letters at the tops of the columns in the figure refer to the stages of plant growth: *B*—blooming, *V*—height of vegetative development, *Dg*—initial vegetative degeneration, *D*—death.



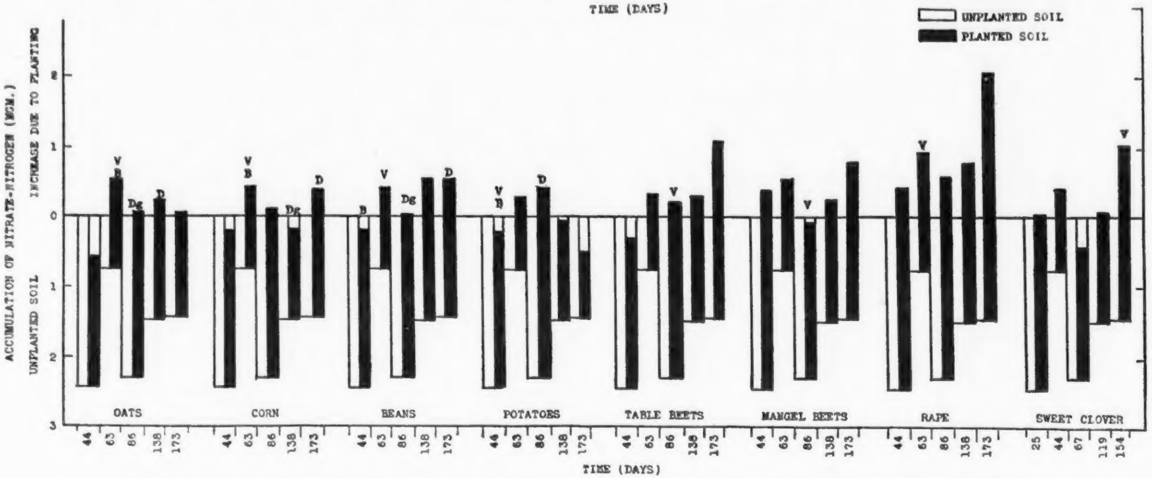


FIG. 1 ABOVE. INFLUENCE OF PLANT DEVELOPMENT UPON THE EVOLUTION OF CARBON DIOXIDE FROM THE SOIL

FIG. 2 BELOW. INFLUENCE OF PLANT DEVELOPMENT UPON THE CAPACITY OF SOILS TO FORM NITRATE FROM THE SOIL NITROGEN

(Letters at the tops of the columns refer to stages of plant growth: *B*—blooming, *V*—height of vegetative development, *Dg*—initial degeneration, *D*—death)

There are many features of these results which show similarities to the changes in abundance of the bacterial population and organisms of the *B. radiobacter* group reported previously (7).

All of the plants caused increases in the evolution of carbon dioxide but the course of the formation of the gas appears to be distinct for each of the plants and related to differences in characteristics of growth of the plants, particularly of the plants in the field. All plants influence the transformation to a slight degree in the early stages of growth. In fact, in many cases at the first period of sampling, the planted soils gave off even less carbon dioxide than the unplanted soils. It was quite striking in many cases, what an abundance of plant roots might permeate the soils in early stages of plant growth without exerting any noticeable effects upon either the abundance of organisms or the evolution of carbon dioxide. The plants may be divided into two distinct groups on the basis of their influences upon carbon dioxide production subsequent to the initial period of sampling. The first group includes plants which mature in a single year. The second group includes plants which require more than one year to mature. The first group is represented by oats, corn, beans, and potatoes. These plants in all cases produced the most marked influence upon evolution of carbon dioxide at the second period of sampling. At this time these plants were well advanced in growth and were either at maximum vegetative development or had passed this stage. Subsequent to this period, during phases of degeneration, the influences upon formation of carbon dioxide were less pronounced. The plants exerted even less influence upon the process subsequent to their death.

The second group of plants is represented by table beets, mangel beets, rape, and sweet clover. Even though the formation of carbon dioxide was greatly increased under these plants subsequent to the first period of sampling, this favorable influence did not decrease as time advanced. In fact, at the time of the last sampling the effects were greater than at any previous period. This was particularly striking in the case of the sweet clover. The fact that these biennials were as vigorous in vegetative development at the final period of sampling as at any previous period is undoubtedly largely responsible for the continued high level of formation of carbon dioxide under these plants.

It is quite apparent that the formation of carbon dioxide in the unplanted soil in the field decreased progressively throughout the period of study. This suggests that the decomposable organic matter in unplanted soil becomes depleted to a marked degree within a single season.

Whatever factors are responsible for increasing the production of carbon dioxide in soils under plants, continue to be active as long as the plants are developing. The factors are apparently regulated by physiological characteristics associated with growth and senescence of the plants.

It seems particularly suggestive that microörganisms may evolve considerably greater amounts of carbon dioxide from soils supporting root growth than

FIG. 2 BELOW. INFLUENCE OF PLANT DEVELOPMENT UPON THE CAPACITY OF SOILS TO FORM NITRATE FROM THE SOIL NITROGEN
(Letters at the tops of the columns refer to stages of plant growth: *B*—blooming, *V*—height of vegetative development, *Dg*—initial degeneration, *D*—death)

from soils containing no roots. This is particularly significant in view of the fact that this increase is associated with periods of active development of the plants, particularly the periods of maximum vegetative development, blooming or early vegetative degeneration. Since this is the case it would seem to be logical to conclude that at least part of the increase in carbon dioxide in the soil air under plants and increase in bicarbonates about plant roots should be ascribed to microbial action and not entirely to respiration of the plant roots as assumed by Barakov, Turpin, and Metzger. What portion of the total increase in carbon dioxide under plants is due to the microörganisms is uncertain, this may be a relatively slight or large proportional amount. At least, formation of carbon dioxide by the microörganisms follows much the same course of changes as the total increases and decreases of the gas under plants.

As regards the importance of microörganisms about plant roots as factors affecting the feeding power of plants, it appears likely that with annuals they exert very ltttle greater effects upon the solubility of nutrients in soils supporting plants than in soils supporting no plants. This appears probable in view of the fact that the acceleration of biological activities, being dependent upon contributions from the plants, becomes progressively greater as the plants mature, and reaches its highest point only at periods subsequent to maximum vegetative development. The requirements of the plants for soil nutrients follow an inverse course, being greater in the early stages of development and decreasing when microbial activities appear to be greatest. Under plants developing over longer periods of time, as in the case of biennials, the microbial activities are at a high level long before flowering and seed development and may exert much greater effects upon the solubility of soil nutrients about roots than in fallow soils during vegetative growth. Even in these instances, however, maximum vegetative development and consequently absorption of nutrients, occur before the most pronounced effects of the plants are exerted upon the microörganisms.

Nitrification of the soil nitrogen

The data presented in table 2 and figure 2 indicate the amounts of nitrate-nitrogen formed during the periods of incubation indicated in the table. The data represent the differences between the amounts of nitrate-nitrogen found in the soils at the termination of the incubation period and the amounts present at the time that the soils were sampled. The results from the soils sampled at the second period are not directly comparable with the others since they represent nitrate formation during a shorter period of time.

Although nitrate formation from these soils was not influenced to as great a proportional degree by plant development as were the numbers of certain groups of bacteria, it was significantly modified and in somewhat the same manner as the evolution of carbon dioxide. At the first period of sampling,

some of the biennials were the only plants which brought about greater nitrification in the soil than occurred in the absence of plant growth. The influence of the annuals was erratic at subsequent periods of study, but in most cases while the plants were alive, the accumulation of nitrates was greater in the soils which supported root growth. The formation of nitrates appeared to be affected by the beans to a greater extent and more consistently than by any of the other annuals. As with their influence upon the bacterial population, the potatoes showed less extended favorable effects upon nitrification than any of the other plants. This may be correlated with the short period of growth of the potatoes.

Nitrification was much more active in soils under biennials than under annuals and the duration of this effect extended throughout the season. At the last period, nitrification was greater under the biennials than at any previous period with any of the plants. Rape exerted the most pronounced effects throughout the study. Although the sweet clover showed little effect until the last sampling, this may be because this plant grows more slowly than any of the other plants and had only reached the stage of vigorous and abundant vegetative growth at the end of the season.

TABLE 2

*Accumulation of nitrate-nitrogen in fallow soil and in soils obtained from the roots of various plants**

PLANT	AGE OF PLANT DEVELOPMENT					AVERAGE OF ALL PERIODS
	44 days	63 days	86 days	138 days	173 days	
Fallow	2.44	0.75	2.29	1.49	1.46	1.69
Oats	1.87	1.30	2.37	1.73	1.51	1.76
Corn	2.24	1.19	2.41	1.33	1.85	1.80
Beans	2.26	1.16	2.31	2.05	2.02	1.96
Potatoes	2.24	1.03	2.72	1.47	0.98	1.69
Table beets	2.15	1.11	2.52	1.83	2.57	2.04
Mangel beets	2.84	1.32	2.23	1.76	2.29	2.09
Rape	2.87	1.67	2.90	2.30	3.56	2.66
Sweet clover†	2.48	1.15	1.88	1.58	2.48	1.91
Period of incubation (days)	30	18	31	28	30	....

* Mgm. of nitrate-nitrogen per 100 gm. of dry soil.

† For sweet clover the incubation periods are 25,44, 67, 119, and 154 days.

It seems justifiable to conclude that accumulation of nitrates is more rapid in soils obtained from plant roots than from soils supporting no plant growth. At least such is the case at certain stages in the growth of all the plants which were studied. It is not clearly apparent from these observations what differences are exerted by the plants at different stages of growth except that the greatest accumulation occurs during periods of growth of the plants and consequently persists for longer times under biennials than annuals. No marked differences were observed between the action of legumes and non-legumes

which could not be explained as being correlated with differences in duration of vegetative growth. It is quite possible that the development of higher plants increases the abundance of nitrifying organisms in soils although the method which was used for studying nitrification is not devised to detect such effects. An increase in the rapidity of accumulation of nitrates by this method of study does indicate, however, that certain portions of the soil organic matter

TABLE 3

Disappearance of ammoniacal-nitrogen and formation of nitrate-nitrogen from ammonium sulfate added to fallow soil and soils obtained from the roots of various plants

PLANT	AGE OF PLANT DEVELOPMENT					AVERAGE OF ALL PERIODS
	44 days	63 days	86 days	138 days	173 days	
*Ammoniacal-nitrogen consumed**						
Fallow	29.9	27.0	10.8	5.6	13.6	17.4
Oats	30.1	29.7	10.4	7.3	14.8	18.5
Corn	30.1	27.5	10.4	8.6	16.2	18.6
Beans	29.6	26.9	12.1	10.0	17.2	19.2
Potatoes	29.3	27.3	10.0	6.6	13.6	17.4
Table beets	28.2	24.9	12.9	9.1	15.0	18.0
Mangel beets	29.3	26.3	12.0	9.4	14.9	18.4
Rape	30.1	27.7	13.1	10.4	15.1	19.3
Sweet clover†	29.7	26.6	10.2	8.9	14.4	18.0
*Nitrate-nitrogen formed**						
Fallow	30.38	23.86	7.59	4.90	12.47	15.84
Oats	28.60	25.05	8.20	5.08	13.60	16.11
Corn	31.82	22.67	4.55	6.11	13.45	15.72
Beans	29.46	23.15	10.39	6.88	14.03	16.78
Potatoes	27.63	23.09	8.29	5.64	12.01	15.33
Table beets	27.75	20.10	8.45	6.71	13.13	15.23
Mangel beets	27.26	21.18	9.75	7.20	13.07	15.69
Rape	29.43	24.05	10.67	7.17	17.07	17.68
Sweet clover†	27.33	21.83	8.44	5.57	13.39	15.31
Period of incubation (days)	30	18	5	5	5	....

* Mgm. of nitrogen per 100 gm. of dry soil.

† For sweet clover the incubation periods are 25, 44, 67, 119 and 154 days.

are undergoing more rapid decomposition and that these organic materials are of fairly narrow carbon-nitrogen ratios. In view of these assumptions it appears likely that the plants have added this organic matter to the soil. Since the effects appear previous to the death of the plants it seems likely that considerable amounts of such organic materials may be added to the soil during certain phases of root development. These conclusions are further emphasized by the results of the observations upon the abundance of the microörganisms

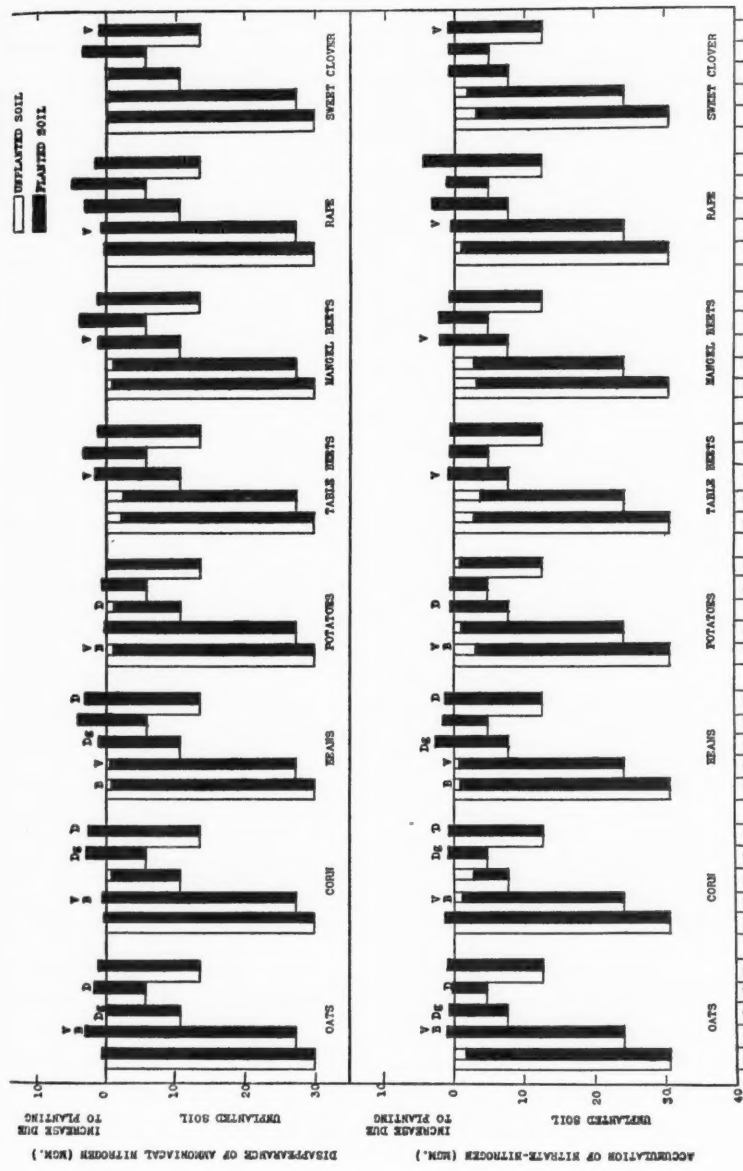


FIG. 3. INFLUENCE OF PLANT DEVELOPMENT UPON THE CAPACITY OF SOILS TO TRANSFORM AMMONIACAL-NITROGEN

(Letters at the tops of the columns refer to stages of plant growth: *B*—blooming, *V*—height of vegetative development, *Dg*—initial degeneration, *D*—death)

in the soils (7), and upon the formations of carbon dioxide from the soils. These studies seem to suggest that during the time when plants are developing in the field, nitrification proceeds at a more rapid rate about the roots at certain stages in their development than in fallow soils, in spite of the fact that greater amounts of nitrate-nitrogen are detected in fallow soils.

If the second period of sampling is left out of consideration (this appears justified since the incubation period was much shorter than for the other soils) it seems clearly apparent from the figure that accumulation of nitrate-nitrogen in the unplanted soil becomes slower with the passage of time. At the first sampling, 2.44 mgm. of nitrate-nitrogen were formed in 30 days. At the last sampling, 129 days later, only 1.46 mgm. were produced.

Nitrification of ammonium sulfate

Nitrification of ammoniacal-nitrogen added to soils may be determined by measuring both the amounts of nitrate-nitrogen formed and the ammoniacal-nitrogen consumed after certain periods of incubation. Both methods have been used in the present study. The data are presented in table 3 and figure 3. During the first observations the soils were incubated for 30 days before the extent of nitrification was determined. This proved to be too long a period of time since practically all of the ammoniacal-nitrogen was oxidized to nitrate-nitrogen and any differences which might have existed between the planted and unplanted soils were obscured. Even an incubation period of 18 days, which was used with the soils at the second sampling, proved too long. Nitrification in the soils of the last three samplings was determined after incubation for 5 days. Results of these last observations show some slight influences of development of plants upon nitrification of ammonia. Greater nitrification is apparent if the process is measured by disappearance of ammonia than by formation of nitrate. In fact, except with the beans, mangel beets, and rape, it would appear that the plants exerted no detectable influence on nitrification of ammonium sulfate as measured by formation of nitrate. On the other hand, if disappearance of ammonia is considered, it appears that in the last three periods of study all of the plants except potatoes increased nitrification. The explanation for the differences between nitrate formation and ammonia disappearance does not appear to be clear. It might be assumed that the development of higher plants introduced into the soils appreciable amounts of decomposable organic material containing very little nitrogen. In the decomposition of such substances microörganisms would assimilate some of the available ammoniacal nitrogen. However, such an explanation does not seem logical in view of the fact that nitrate-nitrogen accumulated in considerable amounts during the incubation of these soils where no substances were added. It is quite possible that some of the ammonia or nitrate became physically attached in the soil and was not detected by the

methods used for its estimation. Whatever factors were active, exerted a more pronounced effect in the planted soils.

Provided that nitrification of ammonium sulfate was more rapid in soils obtained from plant roots than from fallow soils it seems likely that this might be ascribed to the presence of a more active nitrifying population. The moisture content of all of the soils was kept the same, the temperatures of incubation were identical and the reactions were practically the same in all cases. Assuming that the activity of the organisms at the time of sampling was the controlling factor, it is reasonable to expect that differences between the soils would be eliminated after prolonged incubation subsequent to the addition of ammonium sulfate. Differences would be expected only in the first few days after the addition of ammonia. Such has proved to be the case. Although no conclusions can be drawn concerning the periods at which nitrification is most rapid or concerning the factors involved, it does appear that development of practically all of the plants has resulted in the appearance of a more active nitrifying flora. As in the other biological studies, the potatoes produced the slightest effects and the rape the most marked influences.

SUMMARY

Results are reported of the influences of the development of higher plants upon certain activities of microörganisms in soils. Measurements were made of the amounts of carbon dioxide formed by the microörganisms, of the amounts of nitrate-nitrogen produced from the soil organic matter, and of the nitrification of ammonium sulfate. The measurements were made periodically during the growth of plants cultivated both in the field and greenhouse. The following effects were apparent:

1. The evolution of carbon dioxide was greater from soils which supported plant growth and the course of the formation of the gas during the season was distinct for each of the plants and related to growth characteristics of the plants.
2. The course of the influences of the plants on the formation of carbon dioxide was much the same as the course of changes in the bacterial population in the soil. The plants exerted slight effects in the early stages of growth, maximum effects at advanced vegetative development and fruiting, and less pronounced effects subsequent to degeneration and death. Because of their more prolonged development, biennials raised the level of carbon dioxide production over longer periods of time than did the annuals.
3. The evolution of carbon dioxide in unplanted soil decreased as the season advanced.
4. Nitrification of the soil nitrogen was affected in somewhat the same manner as was evolution of carbon dioxide. Nitrates accumulated more rapidly in soils which supported growth of plants, and the enhanced effects of plants were apparent during advanced stages of growth.
5. Nitrification of ammonium sulfate in the soils did not appear to be affected by plant development to so great an extent as nitrification of the soil nitrogen. During the early stages of the transformation, ammonia disappeared more rapidly in the soils which supported plant growth but the differences became obscured during extended periods of incubation.

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The influences of plants upon this process appear to be more striking if the transformation is studied by determining the disappearance of ammonia than by determining the formation of nitrate.

6. The acceleration in evolution of carbon dioxide and nitrification of the soil nitrogen is believed to be the result of the addition of organic substances to the soil by the growing plants. It seems likely that these organic materials have relatively narrow carbon-nitrogen ratios. Transformation of these plant materials may be responsible for increasing the activity of the nitrifying flora.

7. The course of the influences of the plants upon the evolution of carbon dioxide by the soil organisms suggests that the microörganisms are important agents in increasing the carbon dioxide in the soil and the bicarbonates about roots during plant development.

8. The plants increase the activities of soil organisms to a pronounced degree after the periods of maximum absorption of nutrients by the plants. Consequently the availability of the nutrients in fallow soils may be much the same as their availability in planted soils during the periods when these substances are required in greatest abundance by the growing plants.

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IS SULFUR A LIMITING FACTOR OF CROP PRODUCTION IN SOME UTAH SOILS?[1]

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Received for publication February 27, 1929

Sulfur is an essential constituent of the bodies of plants and animals. Like nitrogen in its cycle, sulfur journeys through earth, air, and water, occurring in both the organic and the inorganic forms. Native nitrogen occurs in the atmosphere, native sulfur in soil and water. Sulfur and nitrogen find their way into the atmosphere through combustion and decay; they both are rendered available to the growing plants through biological processes. Animals require both nitrogen and sulfur in the organic form. A vast amount of work has been done on the nitrogen cycle, much less on the sulfur cycle. This is because of the different values which have been assigned to the two processes. Three modern discoveries, however, have given to the sulfur cycle a new interest: 1. Modern methods of analysis have shown that sulfur constitutes a greater proportion of plant and animal tissues than was formerly believed to be the case. 2. Soils have been found which contain insufficient sulfur to meet the needs of the growing plants. 3. It has been learned that sulfur may play an indirect rôle in the liberation of plant-food. With these facts in mind, a study has been made of: (*a*) The sulfur content of a limited area of the Cache Valley soils; (*b*) the sulfur removed from these soils by growing crops; (*c*) the quantity of sulfur brought to the soil by rain and irrigation waters; (*d*) the influence of sulfur carriers upon the bacterial activity of the soil, and (*e*) the influence of sulfur on the yield of barley.

SULFUR IN SOIL

Soils were collected from various localities in Cache Valley and analyzed for total sulfur. The samples were taken to a depth of 12 inches, great care being taken to see that a representative sample was obtained from each district. The total sulfur in the soil was determined by the moist-fusion method (2). The averages of closely agreeing determinations are given in table 1.

Two facts are evident from these results: First, there is a wide variation in the sulfur content of Cache Valley soils; second, the sulfur content of some of these soils is very low. This becomes evident in comparison with the sulfur

[1] Contribution from the department of bacteriology and chemistry, and department of physics. Publication authorized by director, February 21, 1929.

[2] It is a pleasure to acknowledge the kind assistance of C. T. Hirst, D. H. Nelson, J. Dudley Greaves, Lester Hirst, and Yeppa Lund in the analytical work.

content of soils from other parts of the United States. The soils of Missouri (5) were found to contain from 297 to 1067 pounds per acre-foot of soil. Iowa (3), 700 to 900; Oregon (16), 720 to 1200; Wisconsin (12), 660 to 2000; Nebraska (1), 828 to 2526; Kentucky (18), 900 to 2340; Kansas (20), 972 to 1656; Tennessee (15), 1850; and the average for the eastern part of the United States (17) is 1440 pounds per acre-foot of 3,600,000 pounds. These have all been calculated on the same bases as the Cache Valley soil, 3,600,000 pounds of soil per acre-foot. The sulfur content of the Greenville soil is lower than any of these, and all but two of the Cache Valley soils contain less sulfur than the average of the eastern part of the United States. The average for the Cache Valley soils is only 903 pounds per acre-foot. Oregon, Wisconsin, Iowa, and Missouri, all of which have been considered by some workers as deficient in sulfur, contain more sulfur than Cache Valley soils.

TABLE 1

Percentages and pounds per acre of sulfur in typical Cache Valley soils

LOCALITY	SULFUR	SULFUR IN 3,600,000 POUNDS SOIL
	per cent	*pounds*
Greenville Experiment Farm	0.007	252
Smithfield	0.014	504
Lewiston	0.019	684
Cache Junction	0.019	684
Avon	0.020	720
Trenton	0.023	828
Hyrum	0.024	864
Cornish	0.025	900
Richmond	0.033	1,188
Newton	0.043	1,548
Petersboro	0.049	1,764

A general estimation of the durability of a soil may be obtained by comparing the quantity of sulfur it contains plus its gain from various sources with the yearly sulfur loss. Table 2 indicates the quantity of sulfur removed yearly from the soil by maximum crops. In the case of wheat, oats, barley, and corn, the data have been obtained from average results obtained by the analyses of numerous samples grown under varying conditions in different sections of Utah (11). The sulfur content of the grains varied widely, depending upon variety, soil, and whether or not irrigation water was used. Therefore, under varying conditions, more or less sulfur may be removed by the same crop than is indicated by the figures given in table 2, but they may be taken as close approximations of what may be expected under general conditions. The sulfur in the other crops has been calculated from the work of Hart and Peterson (12). The determinations by these, as well as those by the present workers, were obtained by the moist-fusion method; consequently, they represent the

sulfur removed by the plants. This was not the case where the analyses were made on the ash.

It is evident that the sulfur removed annually from the soil varies widely with the crop. A 300-bushel crop of potatoes removes only 5 pounds, whereas an 8-ton crop of alfalfa removes 52.8 pounds. Moreover, it has been shown elsewhere (11) that there may be a great variation in the sulfur content of grain; for example, there was found to be a difference of 230 per cent in the sulfur content of wheat, 255 per cent in the case of oats, and 293 per cent in the case of barley, depending upon whether much or little was available to the growing plant.

TABLE 2

Pounds of sulfur removed from an acre of soil by maximum crops

CROPS	SULFUR
	pounds
Corn grain (100 bu.)	9.5
Corn stover (3 tons)	7.6
Total crops	17.1
Barley grain (100 bu.)	7.4
Barley straw (2.5 tons)	7.4
Total crops	14.8
Oats grain (100 bu.)	6.1
Oat straw (2.5 tons)	6.0
Total crops	12.1
Alfalfa (8 tons)	52.8
Peas (4 tons)	13.6
Sugar beets (20 tons)	13.0
Potatoes (300 bu.)	5.0

The exact nature of the process of assimilation of sulfur or other plant-food substance from the soil is not known. It may perhaps be assumed, however, without serious error that the rate of increase of crop yield with increase in sulfur is proportional to the magnitude of the sulfur deficiency in the soil. In order to obtain a first approximation as to the nature of the influence of sulfur on crop yield, it is doubtless appropriate also to assume that the time rate of depletion of sulfur (on the supposition that none is added from outside sources) is proportional to the product of the sulfur content of the soil and the crop yield. These two hypotheses lead to the conclusion that the crop yield will diminish from year to year at a rate dependent upon the nature of the physiological requirement of the plant for this substance as a plant-food and upon the length of time sulfur-requiring plants have been grown upon the soil.

In order that this may be brought out somewhat more quantitatively, the

mathematical development leading to an exponential relationship is here presented in full.

If we introduce the symbols:

y = crop yield per annum,
s = sulfur content of soil,
s_0 = sulfur content of soil required for optimum growth,
k_1 and k_2 represent proportionality constants as yet undetermined,
t = time,

we may set down the following equations expressing the hypotheses named above:

$$dy/ds = k_1 (s_0 - s) \qquad (A)$$
$$ds/dt = -k_2 (sy) \qquad (B)$$

Integrating (A), we obtain

$$y = k_1 (s_0s - s^2/2) + k_3. \qquad (C)$$

Differentiating this equation with respect to the time,

$$dy/dt = k_1 (s_0 - s)\, ds/dt. \qquad (D)$$

Eliminating ds/dt by means of (B), equation (D) becomes

$$dy/dt = -c(s_0 - s)\, sy. \qquad (E)$$

where c is defined as

$$c = k_1k_2.$$

Upon integration equation (E) becomes

$$y = y_0e^{-c \int (s_0 - s)s\, dt} \qquad (F)$$

It is to be noted that the exponent will approach a finite limiting value as s approaches zero, and if the integration constant of equation (c), k_3, is taken as zero, we may conclude that y will approach zero asymptotically. Equation (E) indicates also that the tangent to the curve of equation (F) will be zero when s is at the optimum value s_0, so that we may infer without any attempt to complete the integration of equation (F) that the relationship between y and t will conform to some such family of curves as is represented in figure 1.

As has been shown (4) in connection with a study of the economic application of irrigation water, the sulfur content of the soil should not be allowed to fall below the point determined by the following equation,

$$k_1 (s_0 - s) = e/a \qquad (G)$$

where e represents the cost per unit quantity of sulfur applied and a the value of unit quantity of crop produced. The question, therefore, as to whether

or not sulfur should be added as a fertilizer will depend upon the constant k_1. which will be characteristic of the crop and of the soil, and upon the constants e and a, which will depend upon the locality. The comparatively low content of sulfur in Cache Valley soils and the small amount in the irrigation streams supplying water for parts of the valley indicate that the problem is deserving of careful attention.

SOIL GAINS IN SULFUR

Combustion and decay are constantly liberating gaseous sulfur compounds. Millions of tons of sulfur are thrown into the atmosphere by volcanoes and from chimneys, especially from some manufacturing plants. This sulfur finds

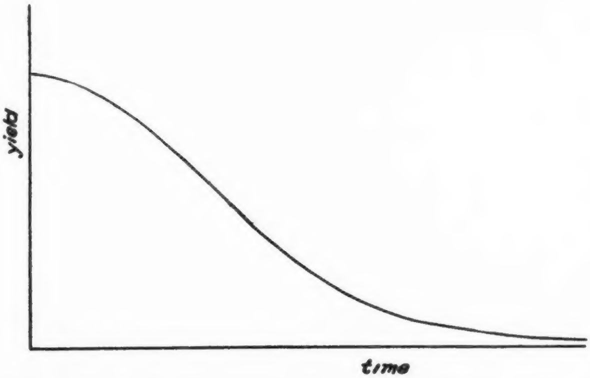

FIG. 1. CURVE ILLUSTRATING DECREASE IN CROP YIELD WITH TIME, AS SULFUR DIMINISHES, AS SHOWN BY EQUATION F

its way back into the oceans, lakes, and streams of the country, and into the soil. The quantity of sulfate discharged into the sea is enormous. The salts of its waters contain about 7.69 per cent of the sulfate radical; consequently, one would expect some sulfur brought to irrigated soils by irrigation waters. The principal irrigation waters of Utah have been analyzed, and in table 3 is indicated the pounds of sulfur brought to the soil by one acre-foot of the specific waters. These results are the averages of many determinations made during different years and seasons of the year; consequently, they represent rather accurately the sulfur which soils may be expected to receive with irrigation waters.

Emery Creek contains 676 pounds of sulfur in an acre-foot of water, Price River, Huntington Creek, Sevier River, Jordan River, and Ferron River all carry over 200 pounds of sulfur in an acre-foot of water. Consequently, none of the lands irrigated with these waters would become deficient in sulfur. These waters are high in alkali salt, however, and because of their high salt

content (10) may be injurious. The water of five streams and one lake tested contained between 100 and 200 pounds of sulfur in an acre-foot of water; seven others carried between 50 and 100 pounds. Twenty-seven streams carried less than 50 pounds, and all but two of these carried less than 25 pounds of sulfur in an acre-foot of water. Consequently, very appreciable quantities of sulfur are carried to the soil by some irrigation waters, and the quantity varies greatly with the streams. Some waters would furnish sufficient for even maximum irrigation crops of even heavy sulfur-requiring plants, whereas

TABLE 3

Amount of sulfur contained in one acre-foot of water from various sources

STREAM	SULFUR PER ACRE-FOOT WATER	STREAM	SULFUR PER ACRE-FOOT WATER
	pounds		*pounds*
Emery Creek	676	Spring Creek	36
Price River	574	Salt Creek	33
Huntington Creek	343	Parley's Creek	37
Sevier River	228	Big Cottonwood	31
Jordan River	205	Provo River	31
Ferron River	203	West Cache Canal	30
Utah Lake	198	Hobble Creek	24
Beaver River	189	Rock Creek	23
Uinta River	184	Weber River	19
Lake Fork	178	Little Cottonwood	19
Green River	165	Parowan Creek	16
Cottonwood	124	North Creek	15
Mill Creek	91	Summit Creek	14
Strawberry	87	Indian Creek	12
Cedar Creek	78	Clear Creek	11
Bear River	76	Ogden River	11
Santa Clara	60	Little Bear River	9
American Fork	54	Box Elder Creek	9
Emigration Creek	50	Red Creek	8
Spanish Fork	49	Summit Creek	7
Ashley	44	Logan River	7
Duchesne	40	Maple Creek	7
Beaver	38	Cub River	3

other waters would carry insufficient quantities but would assist in maintaining the sulfur content of the soil. It is interesting to note that the principal streams of the Cache Valley region, Cub River, Logan River, and Little Bear River carry only small quantities of sulfur. This raises the question: Will soils watered and especially drained by other streams low in sulfur likewise be associated with soils deficient in sulfur? The likelihood is great that this will be the case. The Cache Valley soils irrigated from West Cache Canal and Bear River would receive appreciable quantities of sulfur in the irrigation waters, but the soils watered by the other streams would not.

In addition to the sulfur brought to the soil in irrigation water, there is an annual gain from the atmosphere, brought in by the precipitation. During the years 1924 to 1927, inclusive, samples of rain and snow from the rain gages of the valley were collected after each storm, stored in glass-stoppered bottles, and analyzed twice a year. Samples were collected from ten localities in Cache Valley. The average annual pounds per acre brought to the soil in rain and snow are indicated in table 4.

The high results obtained on the college campus are undoubtedly due to the large quantities of soft sulfur-bearing coal being burned near the rain gauge where the precipitation is collected. The sulfur brought annually to the soil per acre in the other localities varied from 6.4 to 12.1 pounds of sulfur, with an average of 9.5 pounds in the valley. This being an average from nine stations

TABLE 4

Pounds per acre of sulfur carried to soil annually by precipitation

LOCALITY	ANNUAL AMOUNT OF SULFUR PER ACRE
	pounds
College Hill	32.7
Newton	12.1
Hyrum	11.6
Petersboro	10.9
Richmond	10.7
Avon	9.3
Cache Junction	9.1
Lewiston	8.7
Smithfield	6.6
Cornish	6.4

and extending over a period of four years makes it probable that it represents approximately the quantity of sulfur these soils receive annually in the precipitation. An examination of the results reported by Joffe (13) of the sulfur brought to the soil in other places reveals the fact that the results at the Utah station are far lower than those reported for Garforth, England; Leeds, England; Petrograd, Russia; Urbana, Illinois; Ithaca, New York; Tennessee; and Mt. Vernon, Iowa, where the annual amount of sulfur brought to the soil per acre varies from 26 to 131 pounds. These places are located near centers where large quantities of coal are burned; consequently they receive greater quantities of sulfur than would soil in the open country.

The quantity of sulfur brought to the soil in some parts of Russia, Sicily, New Zealand, Rothamsted (England), Samaria, and Wisconsin are nearer the quantity of 6 to 10 pounds per acre brought annually to the Cache Valley soils.

If we assume, therefore, that the sulfur brought to Cache Valley soils annually in the precipitation is 9.5 pounds per acre and 7 pounds per acre annually in the irrigation water (the actual quantity found in the Logan River

water which is used on some of these soils), there would be an annual gain of 16.5 pounds. Where the Cub River water is used on these soils there would be an annual gain of only 12.5 pounds. Where barnyard manure is used there would be sulfur added with the manure. It is likely that the sulfur brought to the soil annually by precipitation and irrigation water would be about sufficient to account for the annual removal in such crops as wheat, oats, barley, corn, peas, and sugar beets. Where crops like alfalfa are grown, the sulfur of the rain and irrigation water would be far from sufficient to meet the needs of the growing plants. Consequently, from these results it may be concluded that with some crops sulfur may become a limiting element in some of the Cache Valley soils, and that at a not-far-distant date.

In all of the preceding calculations no account has been taken of the sulfur lost in drain waters, nor do we have any data on this phase of the subject. The data compiled by Joffe (13), however, show an annual loss of from 8 to 281 pounds of sulfur removed in the drainage water. The quantity lost would vary with the kind of soil, the amount of precipitation, the system of cropping, and the methods of cultivation.

It has been found by Jones (14) that the annual loss of sulfur from drainage in some of the sulfur-poor soils of Oregon, is 15 pounds. Now, if we accept this as an approximation of the loss from the Cache Valley soils and that annually there are 7 pounds brought to the Greenville soil per acre in the irrigation waters and 9.5 pounds in the precipitation, there would remain in the soil 1.5 pounds per acre annually over that removed to supplement the native soil sulfur. Even with crops requiring only small quantities of sulfur this would not meet their need, and with some other crops—alfalfa, for instance—it would be an insignificant quantity. Consequently, these results point to the conclusion that some of the Cache Valley soils will ultimately become deficient in sulfur. The time required for this to become evident will vary with the specific soil, the nature and the size of the crop grown, and the quantity of manure returned to the soil. This is just the opposite of the conclusion reached by Stewart (19) who figures on an annual gain of 45 pounds per acre, which is more comparable to the figure obtained for the precipitation on the college campus. Using the figure, 35 pounds annually, one could conclude with Stewart that sulfur is not a limiting element in crop production.

INFLUENCE OF SULFUR ON SOIL BACTERIA

The small quantity of sulfur in the Greenville soil made it appear probable that, when added to the soil, sulfur would increase its bacterial activities. This was tested by Fife (6) who added sulfur to soils and found that for the short time under observation sulfur had no uniform effect upon the number of bacteria and upon the nitrogen-fixing powers of the soil but that ammonification was increased from 50 to over 100 per cent, depending upon the soil and the amount of sulfur applied. In some cases the nitrification was increased over 100 per cent. These effects could have come from the rapid oxidation

of the sulfur with the production of sulfuric acid, which would increase the available plant nutrients in the soil. For this reason, the influence of sulfur-carrying salts upon the ammonifying, nitrifying, and nitrogen-fixing powers

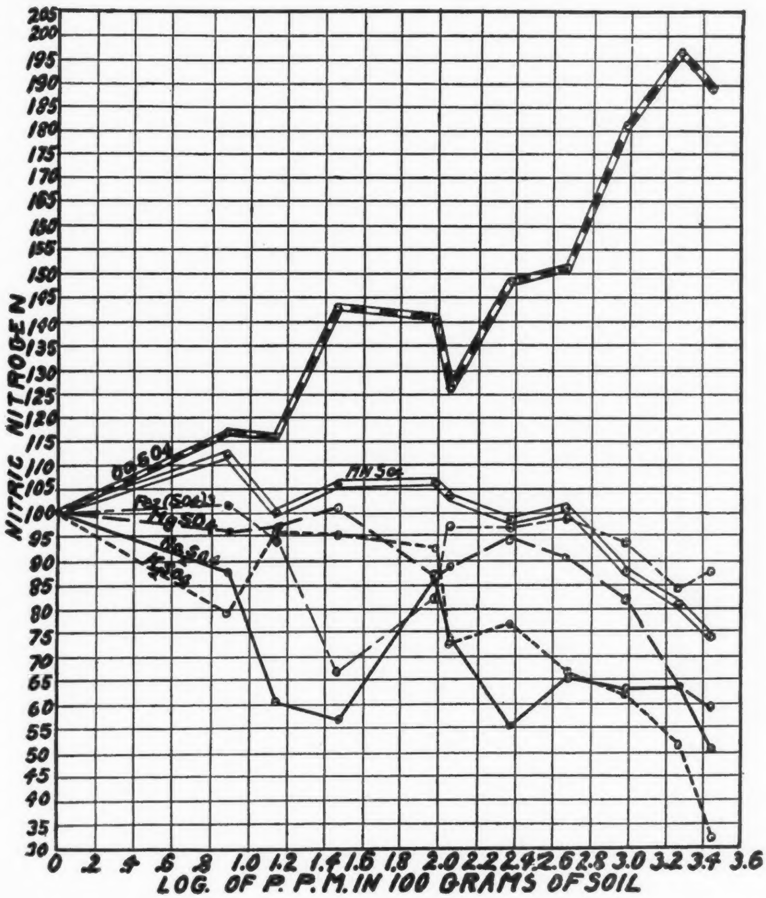

FIG. 2. ILLUSTRATING AMMONIA ACCUMULATION IN SOIL TO WHICH HAVE BEEN ADDED VARYING AMOUNTS AND KINDS OF SULFUR-CARRYING SALTS

of the soil has been determined. The determinations were made by the tumbler method on Greenville soil to which various quantities of the sulfur carriers were added. In the ammonifying and nitrifying tests one per cent of dried blood was added, whereas in the nitrogen-fixation tests one per cent of lactose was added to the soil. The sulfates of sodium, potassium, calcium, magne-

sium, iron, and manganese were used. The average results are given in figure 2. The concentrations of the various salts are stated as the logarithm of parts

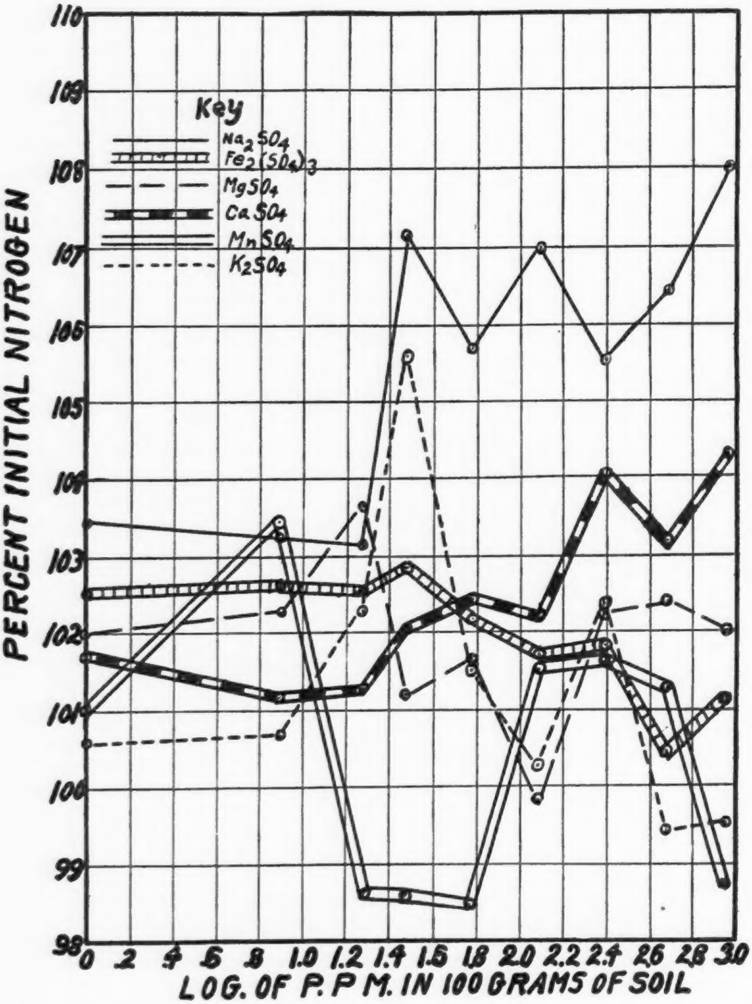

FIG. 3. ILLUSTRATING NITRATE ACCUMULATION IN SOIL TO WHICH HAS BEEN ADDED VARYING AMOUNTS AND KINDS OF SULFUR-CARRYING SALTS

per million of the sulfate ion in 100 gm. of soil. The untreated soil is taken as producing 100 per cent of ammonia. There is a stimulation due to the

manganese, calcium, and iron sulfate but not to the sodium, potassium, and magnesium sulfates, which would lead to the conclusion that the action is probably due to the cation and not the anion.

The results for nitrification are given in figure 3. Both manganese and calcium sulfate stimulate, the latter to a marked extent, but it is likely that the stimulation is due to an indirect action of the salt (9).

The results for nitrogen fixation are given in figure 4. All the sulfates increase nitrogen fixation to a varying degree, depending upon the specific sulfate and the quantity added. In pot experiments extending over a series

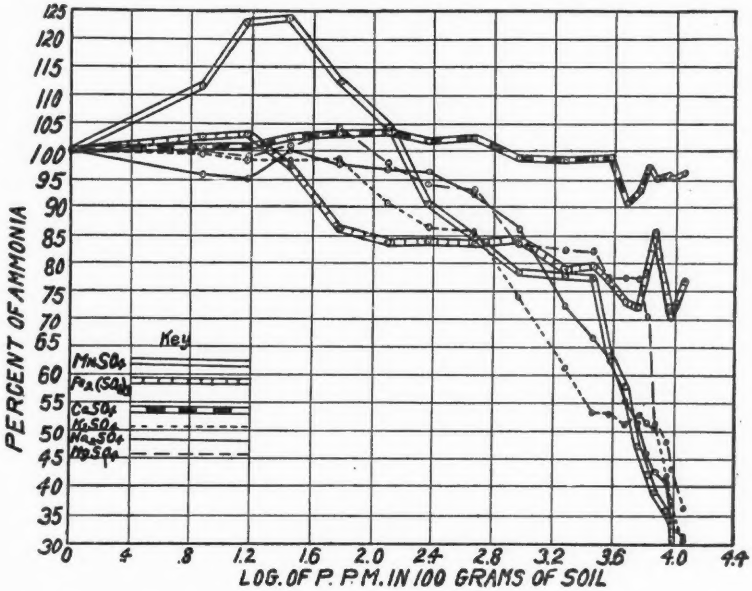

FIG. 4. ILLUSTRATING SOIL GAINS IN NITROGEN WHERE VARYING QUANTITIES AND KINDS OF SULFUR-CARRYING SALTS ARE APPLIED TO THE SOIL

of years it has been shown that the increase in nitrogen is often considerable (8), and it is only in the case of sulfate-treated soils that the typical azotobacter membrane was observed (7). Up to the present, however, pot experiments with barley as the crop have given no regular results from which it might be concluded that sulfur is or is not beneficial.

SUMMARY

An analysis of the Cache Valley soils shows them to contain from 252 to 1764 pounds of sulfur per acre-foot of 3,600,000 pounds. The average sulfur content of the soil analyzed was 903 pounds per acre-foot.

On the basis of certain simplifying assumptions, a mathematical equation is developed indicating the general form of the relationship between the crop yield and the time where no sulfur is added from outside sources.

On the basis of this equation and by means of the law of diminishing returns, a method of determining the critical sulfur content in terms of soil and crop characteristics and economic constants is illustrated.

The quantity of sulfur carried from the soil varies with the crop, the quantity of water applied and the composition of the soil.

Analyses of the water of 45 streams, the waters of which are used for irrigation purposes, showed them to carry from 3 to 676 pounds of sulfur per acre-foot of water. Six streams carried over 200 pounds and 34 streams carried less than 100 pounds. Consequently, the quantity of sulfur carried to the soil by irrigation water is often appreciable. The waters used on the soils of Cache Valley contain only small quantities of sulfur.

The precipitation was collected in ten different localities in the valley. The average annual quantity of sulfur brought to the soil over a period of 4 years at nine of the ten stations varied from 6.4 to 12.1 pounds, with an average of 9.5 pounds. The precipitation collected near the college campus had an average annual sulfur content of 32.7 pounds.

Sulfur-carrying salts increase the bacterial activities of the soil. This is especially pronounced in the case of nitrogen fixation. This may be due either to the direct action of the sulfur as a food, to the microörganisms, or to an indirect action upon insoluble nutrients.

The conclusion is reached that sulfur may become a limiting factor of crop production in some Cache Valley soils. The time required for this to manifest itself in diminished crop returns will vary with the soil, the specific irrigation water used, and the crop grown upon the soil.

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NITRATES IN SOIL AND PLANT AS INDEXES OF THE NITROGEN NEEDS OF A GROWING CROP[1]

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Received for publication March 5, 1929

The Rhode Island Agricultural Experiment Station has been engaged for some time in a series of attempts to determine the feasibility of controlling optimum fertilization of market-garden and field crops by the maintenance of optimum concentrations of mineral nutrients in the plant solution or in the soil extract, as measured by chemical analyses. Two papers have appeared, suggesting tentative minimum concentrations to be exceeded to insure normal yields. In 1927 "The current mineral nutrient content of the plant solution as a possible means of chemical control of optimum fertilization" was discussed by Gilbert and Hardin (2), and in 1928 Smith (7) made suggestions concerning "Desirable soil-nitrate levels for certain market-garden crops."

During the growing season of 1928 further efforts were made to control soil and plant-nitrate levels by side-dressing with soluble nitrogen fertilizers at intervals during the season. This paper is concerned with two aspects of the problem:

1. The 1928 attempts to control nitrate concentrations.
2. A comparison of the soil and plant as sampling sources with regard to their general applicability for the prediction of a future nitrogen need of a crop.

CHEMICAL METHODS

The methods of measuring nitrates have been described in detail elsewhere. The methods used in measuring the nitrate nitrogen in the soil were those of the junior author (7), and determinations of nitrates in the plant solution were made according to the technique described by the senior author (1). The analyses here reported are in terms of nitrate nitrogen in the expressed plant solution and that in oven-dry soil.[2]

GROWTH MEASUREMENTS

It has been realized that in order to approach more definitely any problem which involves the study of modifications in yields some knowledge of the growth curve for each crop is essential. Therefore, study has been given to the problem of how best to measure growth. It was early recognized that the

[1] Contribution No. 378 of the Rhode Island Agricultural Experiment Station.

[2] The plant solution nitrate determinations were made by Donald E. Frear, and J. Eric Blaney assisted in the work with soil.

ideal method must be simple. Actual measurements of cabbage were tried in 1926 and reported by Gilbert, et al. (3), but this method proved too time-consuming and had too high a labor cost for the results obtained.

In 1928 a weekly photographic record of celery, lettuce, and cabbage was taken. In order to obtain comparable records the focal distance must be kept the same from week to week. This was secured by suspending the camera from an extension bolted to the top of a stepladder. By staking off the position of the stepladder and taking the pictures at the same hour, weekly records were obtained. The areas covered by each individual in the cases of cabbage and

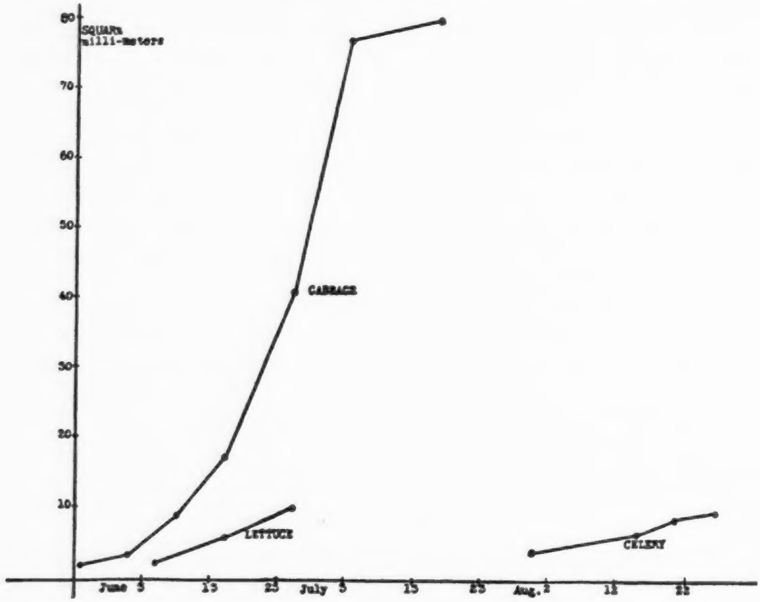

Fig. 1. Growth Curves Based on Photographic Measurements

lettuce, and the row areas with celery were computed by means of caliper measurements made on the photographs. A single plant average per plat was thus secured. These figures were further averaged between plats differing in nitrogen treatments. By this means, weekly points on a curve of growth were obtained (fig. 1). It is recognized that this method of measurement is somewhat rough but it is doubted whether the time and labor involved in the use of a planimeter would justify any small increases in accuracy which might result.

To date this method of measuring growth has proved feasible only with crops which have a horizontal habit of growth. It was tried with corn, but

the results did not warrant further use. As in all experimental work, the number of individuals photographed largely determines the error of the method. Thus, for celery the growth curve can be considered more accurate than for cabbage where only four individuals could be photographed.

AGRONOMICAL DATA

The crops studied were early cabbage, early tomatoes, fall celery, and fall beets. These crops were grown on a permanent 3-year market-garden rotation established in 1916 and described by Hartwell and Crandall (5). Further history of this rotation is given by Smith (7). Table 1 gives a summary of the fertilization during 1928, and also the yields obtained. It will be noted that

TABLE 1

Total fertilization and yields of 1928 market-garden crops

CROP	TREATMENT	CHEMICALS			MANURE-COMPOST	YIELD PER ACRE
		N	P_2O_5	K_2O		
		pounds per acre	*pounds per acre*	*pounds per acre*	*tons per acre*	
Cabbage	Standard	120	100	90	....*	465 barrels
	Low N	60	100	90	....*	423 barrels
Tomatoes	Standard	90	120	90	....†	328 bushels
	Low N	30	120	90	....†	289 bushels
Celery	Standard	90	120	50	26	375 hundredweight
	Low N	30	120	50	26	315 hundredweight
Beets	Standard	75	100	50	....*	335 bushels
	Low N	24	100	50	....*	250 bushels

* Thirty-two tons in each 3-year round; none the cabbage-beet year.

† Green manure annually.

the sole variant was the nitrogen and that a definite increase in yield was obtained where the larger quantities of nitrogen were used. Although a large proportion of the fertilizer nitrogen was ammonia nitrogen, a rapid rate of nitrification usually left only traces of ammonia in the soil, as was shown by ammonia determinations made by Harper's method (4) in soil samples taken weekly.

Early cabbage

Golden Acre cabbage plants were set April 19. The harvest began July 9 and was completed on July 26. The initial fertilizer (table 1) application was made just before the plants were set. No manure was used in the current year, but these plats received a total of 32 tons of manure-compost in each 3-year round of the rotation. The yields were somewhat higher than the 11-year average reported by Hartwell and Crandall (6)

Tomatoes

Murry's New Early Wonder tomato plants were set May 23. The harvest began on July 20 and finished September 7. The tomato crop, as described in this paper, was grown on plats which had been green-manured with buckwheat the previous fall. Although the vine growth was very vigorous, the yields of fruit were somewhat depressed, possibly because of adverse weather conditions which influenced the pollination and thus the set of fruit. Wind injury to the foliage in mid-July may have further reduced the yields.

TABLE 2

Applications of nitrogen during the growing season of 1928

CROP	TREATMENT	INITIAL FERTILIZATION		DATE	SIDE-DRESSINGS		TOTAL N PER ACRE
		$NaNO_3$—N per acre	$(NH_4)_2SO_4$—N per acre		$NaNO_3$—N per acre	$(NH_4)_2SO_4$—N per acre	
		pounds	*pounds*		*pounds*	*pounds*	*pounds*
Cabbage	Standard	9	19	May 17	9	19	28
	Standard	....	....	June 5	9	19	28
	Standard	....	....	June 28	8	17	25
	Low N	5	9	May 17	5	9	14
	Low N	....	....	June 5	6	11	17
Tomatoes	Standard	7	19	July 6	9	19	28
	Standard	....	....	July 25	9	13	22
	Low N	2	5	July 6	3	5	8
Celery	Standard	0	0	August 10	9	19	28
	Standard	....	....	August 31	9	19	28
	Standard	....	....	September 21	12	23	35
	Low N	0	0	August 10	5	6	11
	Low N	....	....	August 31	5	14	19
Beets	Standard	9	19	September 21	9	19	28
	Standard	....	....	October 3	7	13	20
	Low N	4	8	September 21	4	8	12

Celery

Golden Plume celery plants were set July 12, and cut about the middle of October after being boarded during the last week of September

This crop was grown on a stable-manure rotation and the yields were as shown in table 1. These yields, which were exceptionally good as compared with average yields of former years, coupled with growth observations, show that the celery crop was supernormal. This may have been caused by the

rather exceptional moisture conditions during the growth period of celery, brought about by a providential rain at setting time and unusually high precipitation during September and October.

Fall beets

A mixture of Crosby's Egyptian and Early Wonder seed was sown July 31. The beets were pulled late in October. The plats concerned were fertilized following the removal of the early cabbage crop (table 2). The yields obtained were considered to be normal.

CHEMICAL CONTROL

During 1928 an attempt was made to maintain definite levels of nitrogen feeding by applying portions of the nitrogen fertilizer as side-dressings whenever the soil-nitrate determinations indicated them to be necessary. The amounts and dates of applications of side-dressings are given in table 2. Some idea of the effectiveness of this method may be gathered from the graphical description of soil and plant nitrates shown in figure 2. Rapid fluctuations in metabolism in the plant, microbiological action, and nitrate movement in the soil made it impractical and perhaps impossible to control nitrate concentrations except within wide limits. With cabbage, tomatoes, and celery the nitrates in both plant solution and soil were maintained for the plat receiving optimum fertilizer at, or above, the levels recommended by Smith and Gilbert for the greater part of the season. With beets, however, the concentrations were allowed to drop before side-dressings were applied, after which time it seemed difficult to raise the concentrations to those recommended.

Early cabbage

The maximum growth period of cabbage was during the month of June, as is shown by the curve of growth in figure 1. Side-dressings applied May 17 and June 5 influenced the soil-nitrate curve whereas that applied June 28 was reflected by the plant-solution nitrate alone. The depression in the soil-nitrate curve from June 11 forward is of especial interest in the light of high nitrates in the plant during this period. Doubtless the demand of the plant was so great as to rapidly deplete the soil of nitrates. The cabbage crop was in the heading stage during the latter portion of this period and this, without doubt, accounted for the very rapid depletion of the soil even after the extra application of fertilizer nitrogen on July 28. The optimum fertilizer plat had soil-nitrate concentrations above 10 p.p.m. until June 18. For the rest of the season the nitrate nitrogen in plant solution was above the recommended 300 p.p.m.

Tomatoes

The side-dressing of nitrogen which was applied July 6 produced increases in both soil and solution nitrates, whereas that on July 25 did not influence the determinations made on July 30. This is doubtless explained by the fact

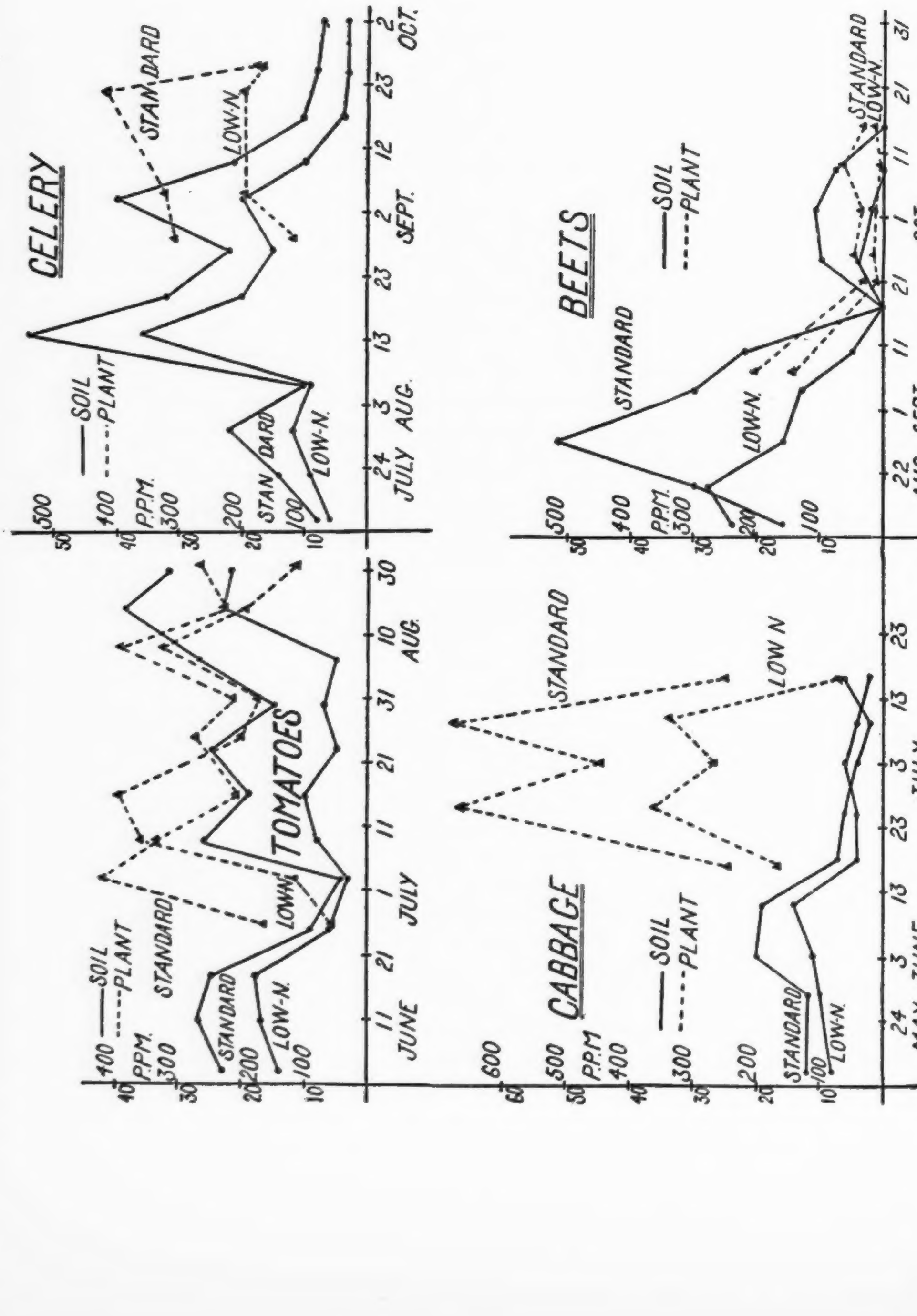

Fig. 2. Comparisons of Standard and Low Nitrogen Treatments as Reflected in 1928 Soil and Plant Determinations of Nitrate Nitrogen

that no rain fell between July 25 and July 30, and the fertilizer had not penetrated the soil. This application appeared in later determinations, as shown in the tomato curve (fig. 2). The nitrate nitrogen of the soil was maintained quite consistently above 20 p.p.m. and that of the solution above 300 p.p.m. for the entire season on the optimum plat (fig. 2).

Celery

The influence of applications of fertilizer on August 10 and August 31 is indicated by the soil-nitrate curve for celery (fig. 2).

The growth curve (fig. 1) of celery shows that there was no very pronounced maximum period during which the celery drew excessively on soil nitrates. Thus the maintenance of levels with this crop should be easier than with a rapidly growing crop such as spring cabbage. Low temperature conditions, during the time when celery would naturally make its greatest demand for nitrogen, were doubtless a factor, since this would slow down metabolism and thus limit the absorption of soil nitrates.

Concentrations of nitrate nitrogen were maintained above the recommended 10 p.p.m. in soil and 300 p.p.m. in plant solution for the greater portion of the season.

Fall beets

With beets, side-dressings were not applied until the soil nitrates were reduced to a trace. The application made on September 21 affected both the soil and solution nitrates, whereas that of October 3 was apparently quickly secured by the plant and, therefore, shows only in the solution curve. Because of the late date at which the first side-dressing was applied, the nitrates in both soil and solution were much below the desired levels for a considerable portion of the growth period.

Except in the case of tomatoes, the optimum fertilizer plats produced crops comparable in yield to the 11-year average of Hartwell and Crandall (6). With beets as an exception, optimum nitrogen fertilizer was correlated with the recommended levels of nitrates in soil and solution and also with higher yields. Beets gave greater yields with the optimum fertilizer than with less nitrogen.

EVALUATION OF METHODS

It is of interest to note that although two methods were used in this attempted control of fertilization, neither of them can be considered to conform perfectly to the demands upon them. An ideal method should, with ease and speed of manipulation, provide accurate indications of the need for further fertilization at any given point in the growth of a crop. A study of the soil-nitrate curves shows that, whereas in the early stages of growth when the demands of the crop were small, the method served to portray accurately the nitrate reserves available to the crop, later in the season the picture was not always clear.

To demonstrate this, curves for the averages of both the soil nitrates and the

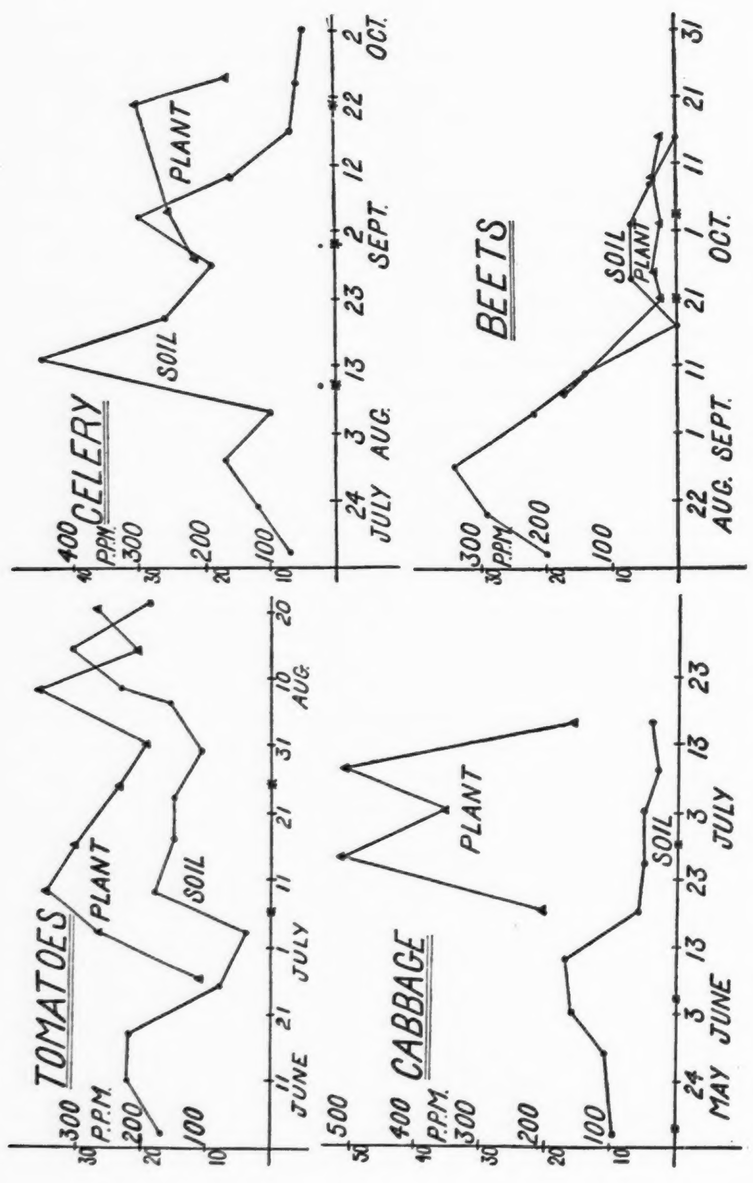

FIG. 3. COMPARISONS OF AVERAGE CURVES OF NITRATE NITROGEN IN SOIL AND PLANTS THROUGHOUT THE 1928 GROWING SEASON

Soil nitrates are indicated on the ordinates by numbers from 0–60 and plant solution nitrates by numbers from 0–600. Dates of fertilizer side-dressings are indicated by stars on the abscissas.

plant-solution nitrates are presented (fig. 3). For tomatoes and beets the curves for soil and crop are nicely correlated but it is evident that the incipient nitrogen starvation, predicted by the low soil nitrates under rapidly growing cabbage and celery late in the season, was contradicted by the abundant nitrate reserve found in the plant. Had reliance been placed on soil conditions alone, nitrogen would have been used in excess of actual needs, and possibly to the detriment of quality in the crop. The soil method insures against nitrogen starvation but does not protect from over-feeding.

Analysis of the plant solution brings the chemist closer to the scene of metabolism and depicts current conditions much more sharply than can a study of the soil. Its disadvantages lie in a more lengthy manipulation and in difficulty in securing sufficient plant material when the crop is small. When the needs justify the labor, and frequent sampling is possible, this method should prove the better of the two.

For the control of nitrogen metabolism a combination of both methods should be superior to either one alone

SUMMARY

In this paper two aspects of the control of fertilization of market-garden crops are discussed.

1. The curves for soil and plant solution nitrates in connection with 1928 crops of cabbage, tomatoes, celery, and beets are given and attention is drawn to the influences of side-dressings of soluble nitrogen fertilizer upon these curves. Nitrate concentrations both in soil and in plant solutions were maintained above previously designated suboptimum concentrations throughout the greater part of the season and yields were uniformly greater than with lower nitrogen fertilization.

2. Control of nitrate concentrations within narrow limits proved impossible.

3. A comparison of the chemical methods used as to their usefulness as indexes of fertilizer need is made. The conclusion is drawn from the data that both methods should be used concurrently in order to secure a complete picture of nitrogen needs.

4. The determination of soil nitrates predicts the nitrogen needs of young plants adequately, but plant solution analyses are more exact for later growth stages.

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THE COMPARATIVE ACID TOLERANCE OF SOME SOUTHERN LEGUMES[1]

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Received for publication March 1, 1929

It is practically a universally accepted fact that legumes are lime-loving plants. They have come to be regarded as lime-loving, not only because they respond favorably in plant growth when grown on neutral soil but also because calcium is a necessary ion in the metabolism of the plant (13, 24). It is also known that the so-called northern legumes, particularly red clover, alfalfa, and sweet clover, are easily affected by soil acidity and that they therefore respond greatly to an application of lime when grown on acid soil. Practical agricultural experience, however, has shown that some legumes, particularly many of the so-called southern varieties, will grow in relatively acid soils without injury to the plant.

A comparative study of the various legumes which would lead to the classification of the varieties on the basis of their acid tolerance would be of value to the farmer. Possibly with this in view some investigations (3, 4, 5) have been made during the past 10 years with red clover, alsike clover, vetch, soybeans, alfalfa, and sweet clover, with the aim, among other things, of determining the exact pH values at which these plants will grow best. This work has done much to clarify thinking in respect to these legume varieties and their relation to soil acidity or alkalinity and thus has helped to give a more definite basis upon which varietal comparisons and recommendations can be made.

In view of the fact that many of the southern grown legume crops differ in variety and in growth response when grown under acid soil conditions from many of the so-called northern legumes, an investigation was undertaken to determine the comparative acid tolerance of the legumes particularly adapted to the southern states. This investigation was primarily a comparative test of the acid tolerance of some of the southern legumes.

EXPERIMENTAL METHODS

It has been shown (5, 19, 23, 24) that the plant will change the reaction of the nutrient medium in which it is growing. To maintain, therefore, a relatively constant H-ion concentration in the cultural solution, would mean

[1] Published with the approval of the dean of the college of agriculture. Research paper 136, Journal Series University of Arkansas.

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the frequent renewal of the solutions as suggested in the above cited work, or else the introduction of an effective buffer. In order to maintain a constant H-ion concentration in the present investigation, pure Ottowa silica sand was used, to which a nutrient solution was added with or without a buffer as described later.

In the first series of the experiment 11,000 gm. of silica sand was used for each 2-gallon glazed jar. The jars were provided with a rubber stopper in which was inserted a glass tube outlet, after the method described by McCall (15). Suction applied to this outlet facilitated the removal of the old nutrient solution before the application of new. In all this work the aim was to maintain a uniform moisture content of the sand. This was done by first removing the excess of old solution by aspirating, and then bringing the jars to a definite weight by the addition of more solution.

Since it was desired to know what effect the H-ion concentration had upon the plant as well as upon the nitrogen-assimilating bacteria, two nutrient solutions were used, one containing nitrogen, the other containing no nitrogen. The plus nitrogen solution was applied to plants not inoculated whereas the minus nitrogen solution was applied to the inoculated plants. To meet the requirement in this experiment a modified form of Tarr and Noble's (23) basal solution was used. The solutions used were as follows:

	MOLECULAR CONCENTRATION	STOCK SOLUTION GRAMS IN 2000 CC.
Solution I:		
$Ca(NO_3)_2 \cdot 4H_2O$	.0182*M*	107.40
$MgSO_4 \cdot 7H_2O$	.0055*M*	33.90
KH_2PO_4	.0064*M*	21.78
K_2HPO_4	.0032*M*	13.694
Solution II:		
$CaSO_4 \cdot 2H_2O$	.0192*M*	82.0
$MgSO_4 \cdot 7H_2O$	.0055*M*	33.9
KH_2PO_4	.0064*M*	21.78
K_2HPO_4	.0032*M*	13.694

For use, 90 cc. of stock solution I, together with 3 cc. of a 0.1 per cent solution of ferric tartrate was made to a volume of 3,200 cc. with distilled water, and applied to uninoculated plants. Similarly 100 cc. of stock solution II, together with 3 cc. of a 0.1 per cent solution of ferric tartrate diluted to 3,200 cc. with distilled water, was added to the inoculated plants.

For the first series the culture solution was varied to include three H-ion concentrations as follows: pH 4.5, 5.8, and 7.0. These concentrations in every case were determined in duplicate. The pH readings were made by the colorimetric method, using the La Mott indicators. Fifth normal sulfuric acid and sodium hydroxide were used in changing the H-ion concentration of the nutrient solution. The amount of nutrient solution added every two days to

each jar ranged from 250 to 300 cc. During the first two weeks of the experiment, no buffer other than the mono- and di-potassium phosphate solution was used. This, however, did not prove sufficient to maintain the pH values during a period of 48 hours, hence a better buffer was introduced, namely, potassium acid pthalate. Tarr and Noble (23) found this a satisfactory buffer when used at a concentration of 0.005 *M*. This concentration was reduced to one-half during the latter part of the experiment. By the use of this buffer the pH values were satisfactorily maintained. No buffer was added to one of the duplicate jars which were maintained at a pH of 7.0, since it was desired to know whether it had any toxic effect on the plants. A comparison of the buffer effect can be made from these jars. It should be noted that the pH of 7.0 was relatively easily maintained, hence, no buffer was actually necessary at this reaction.

Because of the fact that the buffer was found to be toxic to some plants, another series of solution cultures was started in which no potassium acid pthalate was used but where the amount of silica sand per jar was reduced. These jars were watered daily with a very ample amount of nutrient solution. The basic material in the sand was also first removed with concentrated hydrochloric acid, and this acid in turn removed by repeated washing with water. The sand was then placed in 7-inch earthernware jars which had been coated on the inside with paraffin. A modified form of Crone's nutrient solution, the same as that used by Bryan (3), was applied to the jars. His technique was also used in making up the nutrient solution for the noninoculated plants. The modified Crone's solution contained the following chemicals:

	gm.
KCl	100
$CaCO_3 \cdot 2H_2O$	25
$MgSO_4 \cdot 7H_2O$	25
$Ca_3(PO_4)_2$	25
$FePO_4$	25

This solution formula was used for the inoculated plants, but for the uninoculated plants, the $CaCO_3 \cdot 2H_2O$ and $Ca_3(PO_4)_2$ were each reduced to 22 gm., and 25 gm. of $Ca(NO_3)_2 \cdot 7H_2O$ added. In making up either solution 12 gm. of the respective salts were weighed out, placed in a container together with 8 liters of water, thoroughly shaken, and allowed to stand 48 hours. The supernatant solution was then siphoned off and the last portion filtered. The pH was then adjusted to various values and applied daily at the rate of 100 to 150 cc. to each jar. Occasional larger quantities of nutrient solution, made to the proper H-ion concentration were added to the jars in order to help maintain a constant pH.

For the third series of this experiment silt loam field soil was used. The buffer capacity of this soil was determined according to the method used by Runk (22). The collodium bag method (20) was used for obtaining clear soil solutions. The pH of the soil was modified by the addition of 2.3 *N* HCl and

N NaOH or $Ca(OH)_2$. By determining the pH concentration at intervals of one, two, and three days as well as one and two weeks after the addition of an acid or base, it was found that the change in pH did not vary greatly after the third day. However, in this experiment, the pH readings were not taken until two weeks after the addition of acid or alkali. After this period the soil had become stabilized with respect to further pH change.

In order to obtain consistent results the soil was first passed through a 20 mesh sieve. Figure 1 gives graphically the amount of acid or base necessary to give any H-ion concentration desired in this work. In applying the acid or base, 1,300-gm. samples of soil were spread thinly on a large sheet of paper, and the acid or base was then sprayed over the soil with an atomizer. The soil was stirred intermittently. The soil was then placed in 8-inch jars and allowed

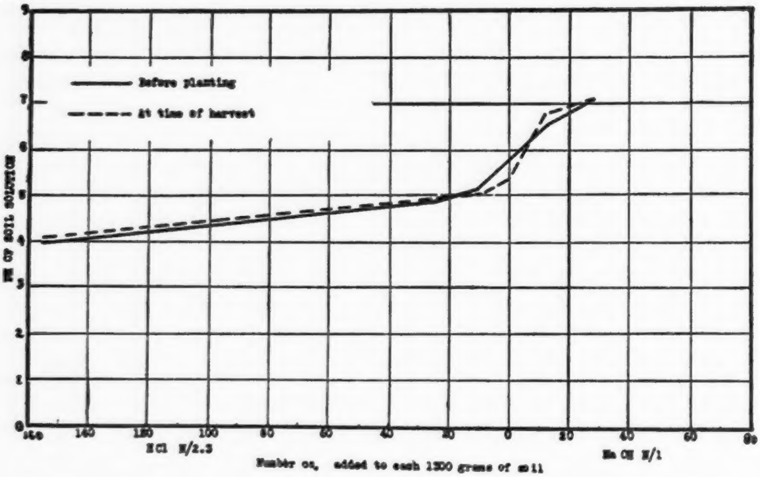

FIG. 1. CHANGE OF SOIL REACTION RESULTING FROM THE ADDITION OF AN ACID OR BASE

to stand two weeks, at which time a pH reading was taken. The legume seed was then planted and a final pH reading made at the time the experiment terminated.

For the first two series of the experiment the legume seeds were first emersed in alcohol in order to cut the surface tension so as to allow a free contact of a 1 to 1000 $HgCl_2$ solution in which they were washed. They were then thoroughly rinsed in distilled water. The seeds of the inoculated series were inoculated with the appropriate bacterial suspension and then germinated between blotters. After germination the vigorous seedlings were planted in the various jars and an additional 150 cc. of strong bacterial suspension was added to the inoculated series. The seeds planted in the plus nitrate jars received the same treatment as described, with the exception that no inocula-

tion was given. The seeds for the third series were sown very heavily in the soil without first germinating them between blotters. The plants were later thinned to six plants to each jar, the weak plants being thereby eliminated.

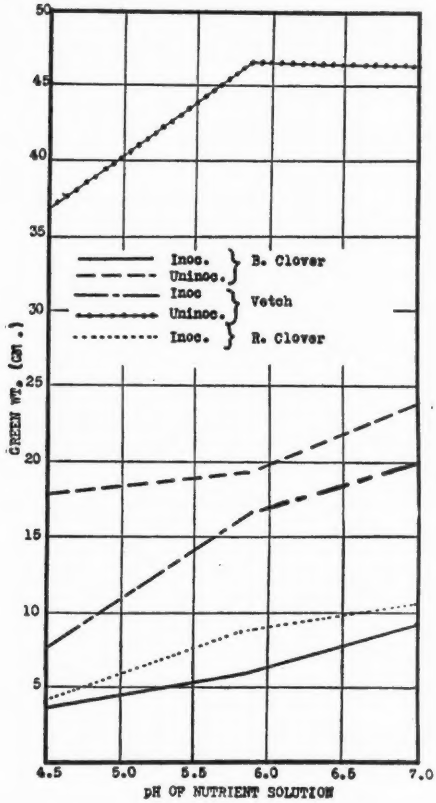

FIG. 2. GREEN WEIGHT OF LEGUME PLANTS GROWN IN SAND CULTURES WATERED WITH A MODIFIED FORM OF TARR AND NOBLE'S NUTRIENT SOLUTION MADE TO VARIOUS H-ION CONCENTRATIONS

RESULTS OF EXPERIMENT

Series I

A modified form of Tarr and Noble's (23) basal culture solution made to various H-ion concentrations was added to the jars of the first series. Red clover, California bur clover, lespedeza, and vetch were planted in these jars. The germinated seedlings were planted rather heavy and later the plants were

TABLE 1

Results from three varieties of legumes grown on nutrient solutions at pH ranges of 4.5, 5.5, and 7.0, and under two variables; inoculated without addition of nitrates; and with no inoculation but with addition of nitrates

(Modification of Tarr and Noble's Basal Solution)

JAR	pH	TREATMENT	LEGUME	TOPS, 5 PLANTS Green weight	TOPS, 5 PLANTS Dry weight	ROOT, DRY WEIGHT OF 5 PLANTS	RELATIVE DEGREE OF INOCULATION PER PLANT	PER CENT NITROGEN IN TOP
				gm.	gm.	gm.		
1	4.5	Inoculated. No nitrate	California bur clover	3.60	0.82	0.06	Could not be determined	2.0
3	4.5	Inoculated. No nitrate	California bur clover	3.40	0.75	0.05	Could not be determined	2.0
5	5.8	Inoculated. No nitrate	California bur clover	6.00	0.85	0.30	Could not be determined	2.4
7	5.8	Inoculated. No nitrate	California bur clover	7.00	1.09	0.30	Could not be determined	2.3
9	7.0	Inoculated. No nitrate	California bur clover	8.05	1.20	0.50	Could not be determined	3.5
11	7.0	Inoculated. No nitrate*	California bur clover	9.70	1.65	0.84	Could not be determined	2.5
2	4.5	Uninoculated. Nitrate	California bur clover	18.50	2.50-	1.00	Could not be determined	Not determined
4	4.5	Uninoculated. Nitrate	California bur clover	17.00	2.55	0.95	Could not be determined	Not determined
6	5.8	Uninoculated. Nitrate	California bur clover	18.40	2.90	1.00	Could not be determined	Not determined
8	5.8	Uninoculated. Nitrate	California bur clover	20.20	3.25	1.20	Could not be determined	Not determined
10	7.0	Uninoculated. Nitrate	California bur clover	23.90	3.42	1.30	Could not be determined	Not determined
12	7.0	Uninoculated. Nitrate*	California bur clover	17.50	2.90	1.00	Could not be determined	Not determined
17	4.5	Inoculated. No nitrate	Red clover	4.32	0.70	0.20	24	2.2
15	4.5	Inoculated. No nitrate	Red clover	4.20	0.80	0.40	26	2.3
13	5.8	Inoculated. No nitrate	Red clover	5.40	0.90	0.41	40	2.5
37	5.8	Inoculated. No nitrate	Red clover	5.50	1.85	0.30	50	2.6
39	7.0	Inoculated. No nitrate*	Red clover	10.50	3.75	0.80	56	3.2
41	7.0	Inoculated. No nitrate	Red clover	3.50	0.70	0.55	50	2.8
14	4.5	Uninoculated. Nitrate	Red clover	3.70	1.15	0.16	....	Not determined
16	4.5	Uninoculated. Nitrate	Red clover	4.00	0.87	0.14	....	Not determined
18	5.8	Uninoculated. Nitrate	Red clover	5.25	1.50	0.20	....	Not determined
38	5.8	Uninoculated. Nitrate	Red clover	7.50	1.40	0.27	....	Not determined

40	7.0	Uninoculated. Nitrate	Red clover	4.50	1.00	0.20	....	Not determined
42	7.0	Uninoculated. Nitrate*	Red clover	8.00	1.60	0.45	....	Not determined
25	4.5	Inoculated. No nitrate	Hairy vetch	7.60	1.50	....	2.0	....
21	4.5	Inoculated. No nitrate	Hairy vetch	7.00	1.30	....	0.0	....
23	5.8	Inoculated. No nitrate	Hairy vetch	16.20	3.24	....	12.5	....
19	5.8	Inoculated. No nitrate	Hairy vetch	17.00	3.30	....	13.0	....
27	7.0	Inoculated. No nitrate	Hairy vetch	20.00	4.00	....	15.0	....
29	7.0	Inoculated. No nitrate*	Hairy vetch	21.00	4.20	....	24.0	....
20	4.5	Uninoculated. Nitrate	Hairy vetch	35.20	6.50	1.05	....	....
22	4.5	Uninoculated. Nitrate	Hairy vetch	40.00	8.00	0.90	....	....
24	5.8	Uninoculated. Nitrate	Hairy vetch	47.00	9.00	0.75	....	....
26	5.8	Uninoculated. Nitrate	Hairy vetch	46.00	8.90	0.55	....	....
28	7.0	Uninoculated. Nitrate	Hairy vetch	46.50	8.80	0.52	....	....
30	7.0	Uninoculated. Nitrate*	Hairy vetch	55.00	11.50	2.60	....	....

* No buffer in culture solution.

thinned to six plants to each jar. The plants were harvested 70 days after planting.

The results from this first series are given in table 1 and in figure 2. The data indicate that the greatest amount of green weight for the tops of red clover and hairy vetch grown in plus nitrate solution was obtained at a pH of 5.5 to 6.0. The same is true for the bur clover plants which were watered with an unbuffered nutrient solution; however, the buffer seems to have stimulated plant growth (see jars 10 and 12, table 1). When the above plants were grown on a minus nitrate solution but inoculated, the greatest green weights of tops were obtained at a H-ion concentration of pH 7.0. Plate 1 shows vetch plants which received a minus and a plus nitrate solution. A comparison of these plants will show that plants grown on a plus nitrate solution developed normally at a pH of 4.5 to 5.8.

The root development of both the inoculated and the uninoculated plants seems to respond better at the neutral range rather than at a higher H-ion concentration. It was difficult to determine the amount of inoculation on the roots of the plants, the percentage never being large. However, an estimate of the percentage inoculation is recorded. It is evident that the greatest inoculation was obtained when the plants were grown in a culture solution having a pH of 7.0.

The results from the lespedeza are not reported because the plants made very poor growth. However, during the brief period of plant growth it was noted that a more normal green plant color was apparent at a pH of 4.5 to 5.0 than at a pH of 7.0. It appeared from these observations that the plant actually functioned more normally in an acid medium.

Series II

As noted under methods, series II was conducted with silica sand which was washed with concentrated hydrochloric acid to remove the basic substances, and then washed with water to remove the acid. No potassium acid pthalate was added to the modified form of Crone's nutrient solution. Velvet bean, spotted bur clover, and seredella plants were used in the second series. The plants were harvested 91 days after planting.

It seems quite evident from the results of this series given in table 2 and shown graphically in figure 3, that the greatest green weight of roots and tops of the velvet bean was made at a pH of 5.8 to 6. This was true for both the inoculated and the uninoculated plants. The reader should be reminded that the cotyledons of the velvet bean are very large and it may be that this latent plant-food stored in the seed affects the plant's capacity to grow in an acid medium.

The seredella and bur clover plants (fig. 3), like the velvet bean, made a greater total green weight of tops and roots at a pH of 5.6 than at 7.0. The cotyledons on the seeds are very small and should therefore not be a serious factor in altering the tolerance of the plant when grown on an acid medium.

Plate 2 shows the relationship of plant growth of seredella and bur clover as affected by hydrogen-ion concentration.

Series III

In series III the plants were grown on a silt loam soil, the pH of which was changed as discussed under methods. In this experiment the soil was adjusted to include seven different pH values. To vary the hydrogen-ion concentration

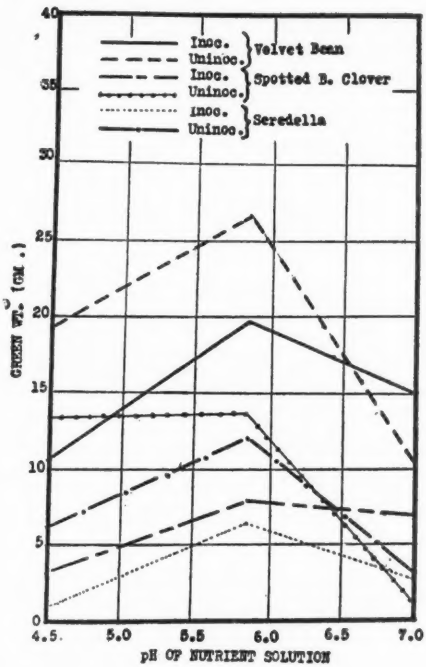

FIG. 3. GREEN WEIGHT OF LEGUME PLANTS GROWN IN SAND CULTURES WATERED WITH CRONE'S NUTRIENT SOLUTION MODIFIED TO INCLUDE VARYING H-ION CONCENTRATION

2.3 *N* hydrochloric acid was used, whereas *N* sodium hydroxide or calcium hydroxide was used for varying the OH ion. Calcium hydroxide was used in comparison with the sodium hydroxide at a pH of 7.0 only.

It appeared to the writer that when plants are grown in culture solutions, the pH values of which are modified so as to include various H-ion concentrations, the natural root environment of the plant is completely changed, and that the results obtained from a comparison of acid tolerance of legumes under such conditions, would not be similar to that which would be obtained in

TABLE 2

Results on the growth of three southern legumes grown at pH values of 4.6, 5.8, and 7.0 on silica sand and watered with Crone's nutrient solution

JAR	pH	TREATMENT	LEGUME	TOPS, 5 PLANTS		ROOT, DRY WEIGHT OF 5 PLANTS	RELATIVE DEGREE OF INOCULATION ON 100 PER CENT
				Green weight	Dry weight		
				gm.	*gm.*	*gm.*	
49	4.5	Inoculated. No nitrate	Velvet beans*	9.2	1.5	1.70	0
50	4.5	Inoculated. No nitrate	Velvet beans	11.7	2.0	3.00	0
53	5.8	Inoculated. No nitrate	Velvet beans	19.7	4.0	2.50	5
54	5.8	Inoculated. No nitrate	Velvet beans	20.1	4.5	1.90	10
57	7.0	Inoculated. No nitrate	Velvet beans	16.0	3.4	3.00	40
58	7.0	Inoculated. No nitrate	Velvet beans	14.0	3.0	1.70	50
51	4.5	Uninoculated. Nitrate	Velvet beans	19.0	4.0	2.17	Not inoculated
52	4.5	Uninoculated. Nitrate	Velvet beans	20.0	4.2	2.17	Not incoulated
55	5.8	Uninoculated. Nitrate	Velvet beans	28.5	6.0	2.95	Not inoculated
56	5.8	Uninoculated. Nitrate	Velvet beans	25.3	5.3	2.95	Not inoculated
59	7.0	Uninoculated. Nitrate	Velvet beans	12.5	1.5	1.05	Not inoculated
60	7.0	Uninoculated. Nitrate	Velvet beans	9.0	2.0	1.05	Not inoculated
61	4.5	Inoculated. No nitrate	Bur clover (spotted)	3.0	1.4	0.20	40
62	4.5	Inoculated. No nitrate	Bur clover (spotted)	3.1	1.8	0.20	50
65	5.8	Inoculated. No nitrate	Bur clover (spotted)	7.5	1.9	0.40	50
66	5.8	Inoculated. No nitrate	Bur clover (spotted)	8.7	2.0	0.50	80
69	7.0	Inoculated. No nitrate	Bur clover (spotted)	5.4	1.7	0.50	90
70	7.0	Inoculated. No nitrate	Bur clover (spotted)	8.7	2.0	0.50	100
63	4.5	Uninoculated. Nitrate	Bur clover (spotted)	15.9	3.0	1.95	Not inoculated
64	4.5	Uninoculated. Nitrate	Bur clover (spotted)	11.0	2.9	1.95	Not inoculated
67	5.8	Uninoculated. Nitrate	Bur clover (spotted)	13.5	3.2	0.90	Not inoculated
68	5.8	Uninoculated. Nitrate	Bur clover (spotted)	13.6	3.0	0.90	Not inoculated
70	7.0	Uninoculated. Nitrate	Bur clover (spotted)	1.5	0.6	0.10	Not inoculated
71	7.0	Uninoculated. Nitrate	Bur clover (spotted)	1.3	0.5	0.10	Not inoculated
73	4.5	Inoculated. No nitrate	Seredella	1.8	0.2	0.75	5

74	4.5	Inoculated. No nitrate	Seredella	1.2	0.2	0.75	5
77	5.8	Inoculated No nitrate	Seredella	6.0	1.8	1.40	20
78	5.8	Inoculated. No nitrate	Seredella	7.0	1.9	1.25	20
81	7.0	Inoculated. No nitrate	Seredella	4.2	0.7	1.40	40
82	7.0	Inoculated. No nitrate	Seredella	3.9	0.9	1.00	40
75	4.5	Uninoculated. Nitrate	Seredella	7.0	1.8	1.15	Not inoculated
76	4.5	Uninoculated. Nitrate	Seredella	6.0	1.5	1.15	Not inoculated
79	5.8	Uninoculated. Nitrate	Seredella	9.0	2.5	1.75	Not inoculated
80	5.8	Uninoculated. Nitrate	Seredella	15.0	3.2	1.75	Not inoculated
83	7.0	Uninoculated. Nitrate	Seredella	4.6	0.7	1.45	Not inoculated
84	7.0	Uninoculated. Nitrate	Seredella	3.9	0.4	1.45	Not inoculated

* Three plants.

TABLE 3

Comparative acid tolerance of some southern varieties of legumes grown on soil having varying degrees of acidity

JAR NUMBER	VARIETY	TREATMENT	pH BEGINNING	pH END	WEIGHT PER 5 PLANTS, TOPS	WEIGHT PER 5 PLANTS, ROOTS	HEIGHT	TYPE OF GROWTH	EMERGENCE*	RELATIVE DEGREE OF INOCULATION
					gm.	*gm.*	*inches*			
3	Bur clover (spotted)	$Ca(OH)_2$	7.0	6.5	1.60	1.65	4	Good	January 20, 1928	Excellent
4	Bur clover (spotted)	$Ca(OH)_2$	7.0	6.5	1.35	2.25	4	Good	January 20, 1928	Excellent
15	Bur clover (spotted)	NaOH	7.0	6.5	1.50	1.20	3	Good	January 20, 1928	Excellent
16	Bur clover (spotted)	NaOH	7.0	6.6	1.50	1.20	3.5	Good	January 20, 1928	Excellent
19	Bur clover (spotted)	NaOH	6.5	6.0	1.00	1.00	3	Fair	January 20, 1928	Fair
20	Bur clover (spotted)	NaOH	6.5	6.0	1.00	1.75	3	Fair	January 20, 1928	Fair
45	Bur clover (spotted)	0	5.9	5.4	0.20	0.30	1	Poor	January 18, 1928	0
46	Bur clover (spotted)	0	5.9	5.4	0.25	0.40	1	Poor	January 18, 1928	0
23	Bur clover (spotted)	HCl	4.9	4.7	0.31	0.31	2	Poor	January 19, 1928	0
24	Bur clover (spotted)	HCl	4.9	4.8	0.30	0.40	2	Poor	January 19, 2928	0
7	Bur clover (spotted)	HCl	4.6	4.4	0.30	0.45	2	Poor	January 19, 2928	0
8	Bur clover (spotted)	HCl	4.6	4.6	0.50	0.46	2	Poor	January 19, 1928	0
11	Bur clover (spotted)	HCl	4.0	4.2	0.20	0.30	2	Poor	January 19, 1928	0
12	Bur clover (spotted)	HCl	4.0	4.2	0.20	0.25	2	Poor	January 19, 1928	0
41	Crimson clover	NaOH	7.0	6.5	2.10	1.00	4	Excellent	January 7, 1928	Good
42	Crimson clover	NaOH	7.0	6.5	2.00	2.30	5	Excellent	January 7, 1928	Good
37	Crimson clover	NaOH	6.5	6.2	3.00	1.70	5	Excellent	January 7, 1928	Good
38	Crimson clover	NaOH	6.5	6.2	3.10	1.50	5	Excellent	January 7, 1928	Good
49	Crimson clover	0	5.9	5.4	3.30	2.50	5	Excellent	January 5, 1928	Excellent
50	Crimson clover	0	5.9	5.4	2.00	2.50	3	Excellent	January 5, 1928	Excellent
33	Crimson clover	HCl	4.6	4.7	0	0	0	Poor	January 6, 1928	0
34	Crimson clover	HCl	4.6	4.7	0	0	0	Poor	January 6, 1928	0
29	Crimson clover	HCl	4.0	4.4	0	0	0	Poor	January 6, 1928	0
30	Crimson clover	HCl	4.0	4.3	0	0	0	Poor	January 6, 1928	0
39	Seredella	NaOH	7.0	6.5	0	0	0	0	0	0

40	Seredella	NaOH	7.0	6.5	0	0	0	0	0	0
35	Seredella	NaOH	6.5	6.0	0.20	0.20	1	Poor	January 8, 1928	0
36	Seredella	NaOH	6.5	6.0	0.15	0.15	1	Poor	January 8, 1928	0
47	Seredella	0	5.9	5.4	0.50	0.50	3	Fair	January 6, 1928	Excellent
48	Seredella	0	5.9	5.4	0.40	0.35	3	Fair	January 6, 1928	Excellent
31	Seredella	HCl	4.6	4.6	0.17	0.10	2	Fair	January 6, 1928	Few
32	Seredella	HCl	4.6	4.6	0.23	0.20	2	Fair	January 6, 1928	Few
27	Seredella	HCl	4.0	4.2	0.12	0.10	2	Fair	January 7, 1928	None
28	Seredella	HCl	4.0	4.2	0.085	0.05	2	Fair	January 7, 1928	None
76	Hairy vetch	$Ca(OH)_2$	7.0	7.4	2.20	2.00	8	Fair	February 16, 1928	Good
77	Hairy vetch	$Ca(OH)_2$	7.0	7.4	2.20	2.30	8	Fair	February 16, 1928	Good
52	Hairy vetch	NaOH	7.0	7.3	2.60	1.60	8	Fair	February 16, 1928	Good
53	Hairy vetch	NaOH	7.0	7.0	3.20	1.90	12	Fair	February 16, 1928	Good
64	Hairy vetch	NaOH	6.5	6.2	6.00	3.00	13	Good	February 16, 1928	Excellent
65	Hairy vetch	NaOH	6.5	6.2	7.5	2.5	18	Good	February 16, 1928	Excellent
88	Hairy vetch	0	5.9	5.4	4.0	2.9	14	Fair	February 16, 1928	Excellent
89	Hairy vetch	0	5.9	5.4	4.3	3.5	18	Fair	February 16, 1928	Good
100	Hairy vetch	HCl	5.3	5.2	3.8	2.5	11	Fair	February 16, 1928	Good
101	Hairy vetch	HCl	5.3	5.2	3.7	2.5	13	Fair	February 16, 1928	Good
112	Hairy vetch	HCl	4.9	5.0	3.2	2.4	11	Fair	February 16, 1928	Good
113	Hairy vetch	HCl	4.9	5.0	3.2	2.0	12	Fair	February 16, 1928	Good
124	Hairy vetch	HCl	4.6	4.7	4.0	1.7	10	Fair	February 20, 1928	Good
125	Hairy vetch	HCl	4.6	4.7	4.0	2.0	12	Fair	February 20, 1928	Few
136	Hairy vetch	HCl	4.0	4.2	1.6	1.6	4	Poor	February 24, 1928	0
137	Hairy vetch	HCl	4.0	4.2	1.4	2.0	4	Poor	February 24, 1928	0
78	Canadian field peas	$Ca(OH)_2$	7.0	7.4	1.5	0.5	19	Poor	February 18, 1928	Poor
79	Canadian field peas	$Ca(OH)_2$	7.0	7.4	1.7	1.5	20	Poor	February 18, 1928	Fair
54	Canadian field peas	NaOH	7.0	7.0	4.05	1.2	36	Good	February 18, 1928	Fair
55	Canadian field peas	NaOH	7.0	7.0	3.3	1.05	34	Good	February 18, 1928	Fair

* Bur clover, crimson clover, and seredella planted January 14, 1928, harvested April 1.
Vetch, sweet clover, Canadian peas, Austrian peas planted February 12, 1928, harvested May 2.

TABLE 3—*Continued.*

JAR NUMBER	VARIETY	TREATMENT	pH BEGINNING	pH END	WEIGHT PER 5 PLANTS, TOPS	WEIGHT PER 5 PLANTS, ROOTS	HEIGHT	TYPE OF GROWTH	EMERGENCE*	RELATIVE DEGREE OF INOCULATION
					gm.	*gm.*	*inches*			
66	Canadian field peas	NaOH	6.5	6.5	7.05	2.1	46	Excellent	February 18, 1928	Excellent
67	Canadian field peas	NaOH	6.5	6.5	5.0	1.9	36	Excellent	February 18, 1928	Excellent
90	Canadian field peas	0	5.9	5.4	5.2	2.0	40	Good	February 18, 1928	Fair
91	Canadian field peas	0	5.9	5.4	4.4	1.9	32	Good	February 18, 1928	Fair
102	Canadian field peas	HCl	5.3	5.3	3.3	1.2	23	Good	February 16, 1928	Fair
103	Canadian field peas	HCl	5.3	5.3	3.6	1.5	31	Good	February 16, 1928	Fair
114	Canadian field peas	HCl	4.9	4.9	1.8	1.5	22	Fair	February 18, 1928	Medium
115	Canadian field peas	HCl	4.9	5.0	1.81	1.2	17	Fair	February 18, 1928	Medium
126	Canadian field peas	HCl	4.6	4.8	1.5	0.9	16		February 18, 1928	Poor
127	Canadian field peas	HCl	4.6	4.8	1.4	0.8	15		February 18, 1928	Poor
138	Canadian field peas	HCl	4.0	4.3	0	0	0	0	February 21, 1928	0
139	Canadian field peas	HCl	4.0	4.2	0	0	0	0	February 21, 1928	0
80	Austrian field peas	$Ca(OH)_2$	7.0	7.5	3.1	3.1	10	Fair	February 16, 1928	Few
81	Austrian field peas	$Ca(OH)_2$	7.0	7.4	2.9	2.9	10	Fair	February 16, 1928	Few
56	Austrian field peas	NaOH	7.0	7.0	2.8	1.9	9	Fair	February 20, 1928	
57	Austrian field peas	NaOH	7.0	7.0	2.5	1.7	7	Fair	February 20, 1928	Good
68	Austrian field peas	NaOH	6.5	6.8	5.6	2.4	16	Good	February 16, 1928	Excellent
69	Austrian field peas	NaOH	6.5	6.6	5.7	2.0	23	Good	February 16, 1928	Excellent
92	Austrian field peas	0	5.9	5.4	3.0	1.6	12	Good	February 16, 1928	Good
93	Austrian field peas	0	5.9	5.4	4.9	2.7	15	Good	February 16, 1928	Good
104	Austrian field peas	HCl	5.3	5.2	3.5	2.4	16	Good	February 14, 1928	Fair
105	Austrian field peas	HCl	5.3	5.2	2.8	1.9	13	Good	February 14, 1928	Fair
116	Austrian field peas	HCl	4.9	4.8	2.5	1.4	7	Good	February 16, 1928	Fair
117	Austrian field peas	HCl	4.9	4.9	2.4	1.4	14	Good	February 16, 1928	Fair
128	Austrian field peas	HCl	4.6	4.6	1.5	1.0	9		February 18, 1928	None
129	Austrian field peas	HCl	4.6	4.7	0.96	1.0	5		February 18, 1928	None

140	Austrian field peas	HCl	4.0	4.4	0.81	1.6	3		February 21, 1928	None
141	Austrian field peas	HCl	4.0	4.2	0.4	1.5	2		February 21, 1928	None
82	Subterranean clover	$Ca(OH)_2$	7.0	7.6	3.0	3.0	2	Fair	February 14, 1928	Poor
83	Subterranean clover	$Ca(OH)_2$	7.0	7.5	3.0	3.5	2	Fair	February 14, 1928	Poor
58	Subterranean clover	NaOH	7.0	7.0	3.8	2.2	2.5	Fair	February 14, 1928	Good
59	Subterranean clover	NaOH	7.0	7.0	5.0	2.6	3.5	Fair	February 14, 1928	Good
70	Subterranean clover	NaOH	6.5	6.5	5.1	2.7	4	Excellent	February 14, 1928	Good
71	Subterranean clover	NaOH	6.5	6.4	5.5	3.0	3	Excellent	February 14, 1928	Fair
94	Subterranean clover	0	5.9	5.5	5.0	2.9	3.5	Excellent	February 14, 1928	Good
95	Subterranean clover	0	5.9	5.6	4.5	3.2	2.5	Excellent	February 14, 1928	Medium
106	Subterranean clover	HCl	5.3	5.2	5.5	4.9	3.0	Excellent	February 14, 1928	Medium
107	Subterranean clover	HCl	5.3	5.4	4.7	4.6	2.5	Excellent	February 14, 1928	Medium
118	Subterranean clover	HCl	4.9	5.2	7.2	6.7	3.5	Excellent	February 14, 1928	Medium
119	Subterranean clover	HCl	4.9	5.2	5.0	7.0	2.5	Excellent	February 14, 1928	Medium
130	Subterranean clover	HCl	4.6	4.7	2.8	2.5	2.5	Fair	February 14, 1928	Medium
131	Subterranean clover	HCl	4.6	4.8	3.8	3.4	3	Fair	February 14, 1928	Medium
142	Subterranean clover	HCl	4.0	4.4	1.0	0.8	1.5	Poor	February 16, 1928	Poor
143	Subterranean clover	HCl	4.0	4.2	1.2	1.3	1.5	Poor	February 16, 2928	Poor
84	White sweet clover biennial	$Ca(OH)_2$	7.0	7.6	2.5	2.7	3.5	Fair	February 14, 1928	Fair
85	White sweet clover biennial	$Ca(OH)_2$	7.0	7.5	2.5	2.5	3.0	Fair	February 14, 1928	Fair
60	White sweet clover biennial	NaOH	7.0	6.8	3.2	3.5	8	Excellent	February 16, 1928	Good
61	White sweet clover biennial	NaOH	7.0	6.8	3.0	3.0	4	Excellent	February 16, 1928	Good
72	White sweet clover biennial	NaOH	6.5	6.7	3.2	3.2	8	Excellent	February 14, 1928	Medium
73	White sweet clover biennial	NaOH	6.5	6.6	3.6	4.5	6	Excellent	February 14, 1928	Medium
96	White sweet clover biennial	0	5.9	5.6	2.4	2.0	4	Good	February 14, 1928	Medium
97	White sweet clover biennial	0	5.9	5.6	2.8	2.0	6	Good	February 14, 1928	Medium
108	White sweet clover biennial	HCl	5.3	5.4	2.2	2.5	5	Fair	February 18, 1928	Medium
109	White sweet clover biennial	HCl	5.3	5.4	2.2	2.7	4.5	Fair	February 18, 1928	Medium
120	White sweet clover biennial	HCl	4.9	5.2	2.0	2.9	4.0	Poor	February 18, 1928	Medium

TABLE 3—*Continued*

JAR NUMBER	VARIETY	TREATMENT	pH BEGINNING	pH END	WEIGHT PER 5 PLANTS, TOPS	WEIGHT PER 5 PLANTS, ROOTS	HEIGHT	TYPE OF GROWTH	EMERGENCE*	RELATIVE DEGREE OF INOCULATION
					gm.	*gm.*	*inches*			
121	White sweet clover biennial	HCl	4.9	5.2	1.7	2.1	3.5	Poor	February 18, 1928	Medium
132	White sweet clover biennial	HCl	4.6	4.7	0.6	0.7	1.5	Poor	February 20, 1928	Poor
133	White sweet clover biennial	HCl	4.6	4.6	1.1	0.9	1.5	Poor	February 20, 1928	Poor
144	White sweet clover biennial	HCl	4.0	4.2	0	0	0		February 21, 1928	0
145	White sweet clover biennial	HCl	4.0	4.2	0	0	0		February 21, 1928	0
86	Hubam	$Ca(OH)_2$	7.0	7.7	3.1	2.7	9	Fair	February 15, 1928	Fair
87	Hubam	$Ca(OH)_2$	7.0	7.8	1.8	2.0	6	Fair	February 15, 1928	Fair
62	Hubam	NaOH	7.0	7.1	4.0	2.6	16	Good	February 18, 1928	Good
63	Hubam	NaOH	7.0	7.2	4.5	3.0	15	Good	February 18, 1928	Good
74	Hubam	NaOH	6.5	6.6	4.2	2.0	15	Good	February 15, 1928	Good
75	Hubam	NaOH	6.5	6.6	4.7	2.0	17	Good	February 15, 1928	Good
98	Hubam	0	5.9	5.6	4.0	2.9	12	Good	February 15, 1928	Good
99	Hubam	0	5.9	5.6	4.3	3.5	14	Good	February 15, 1928	Good
110	Hubam	HCl	5.3	5.4	4.0	2.2	15	Fair	February 19, 1928	Fair
111	Hubam	HCl	5.3	5.4	4.2	2.5	11	Fair	February 19, 1928	Fair
122	Hubam	HCl	4.9	5.2	1.7	1.7	4	Poor	February 19, 1928	0
123	Hubam	HCl	4.9	5.0	2.7	2.4	9	Poor	February 19, 1928	0
134	Hubam	HCl	4.6	4.6	0.8	0.5	2	Poor	February 19, 1928	0
135	Hubam	HCl	4.6	4.5	0.6	0.5	4	Poor	February 19, 1928	0
146	Hubam	HCl	4.0	4.2	0.0	0.0	0	0	February 19, 1928	0
147	Hubam	HCl	4.0	4.2	0.0	0.0	0	0	February 19, 1928	0
	Soybean†	NaOH	8.0	7.0	2.0		8	Fair	November 5, 1927	0
	Soybean	NaOH	7.0	6.4	4.0		10	Good	November 5, 1927	Few
	Soybean	0	5.9	5.6	5.0		12	Good	November 4, 1927	Excellent
	Soybean	HCl	4.5	5.0	1.5		6	Fair	November 4, 1927	0
	Soybean	HCl	3	4.2	0.5		1	Poor	November 4, 1927	0

† Planted November 1, 1927, harvested December 20, weight of 3 plants.

ordinary field soil studies. For this reason the present experiment was conducted in order to make a comparison with the previous sand cultures.

The following legumes were used in this series of experiments. Spotted bur clover, lespedeza, crimson clover, seredella, hairy vetch, Canadian peas, Austrian peas, subterranean clover, Hubam clover, and biennial white sweet clover. The bur clover, crimson clover, and seredella were harvested 77 days after planting whereas the remainder of the varieties were grown 80 days before they were harvested.

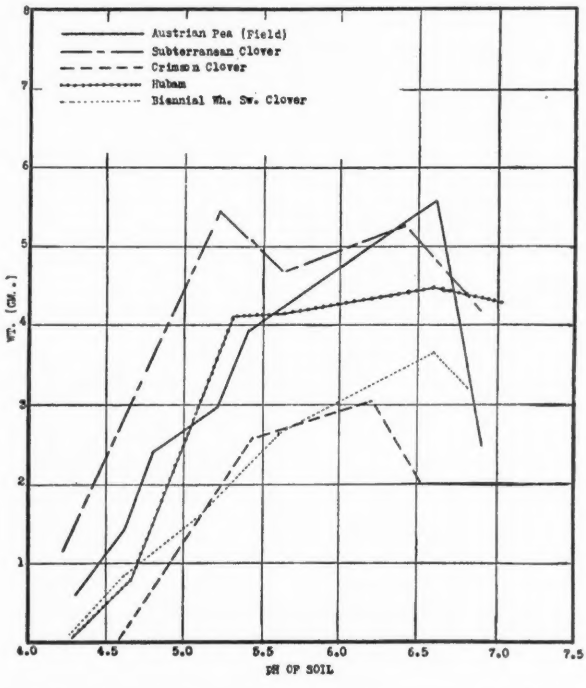

FIG. 4. DRY WEIGHT OF LEGUME PLANTS GROWN ON CLARKSVILLE SILT LOAN, THE pH OF WHICH WAS ARTIFICIALLY MODIFIED

The results from this series are given in table 3. Relative to the rate of plant emergence it will be noted that in most cases a pH of 5.5 to 6.0 was most favorable to the plant. The extreme acid range as well as a slightly alkaline range delayed plant emergence in most cases. The fact that when seeds were sown in an alkaline sand culture they germinated and emerged more slowly than seeds planted at a neutral range, was also noted by Theron (24). Apparently, however, the relationship between the rate of plant emergence and the acidity or alkalinity of the cultural solution in which the seeds are planted depends

somewhat on the variety of seeds used, since, as noted in the table, the Austrian field peas emerged more quickly at a pH of 5.3 than at 7.0, whereas the Hubam clover emerged as soon at a pH of 7.0 as at other ranges on the pH scale.

The dry weights of tops of the various legumes are shown graphically in figures 4 and 5. It is evident from these dry weights that the optimum pH for most of the legumes worked with in soil was 6 to 6.5. Certain legumes, however, as the seredella, spotted bur clover, and possibly the subterranean

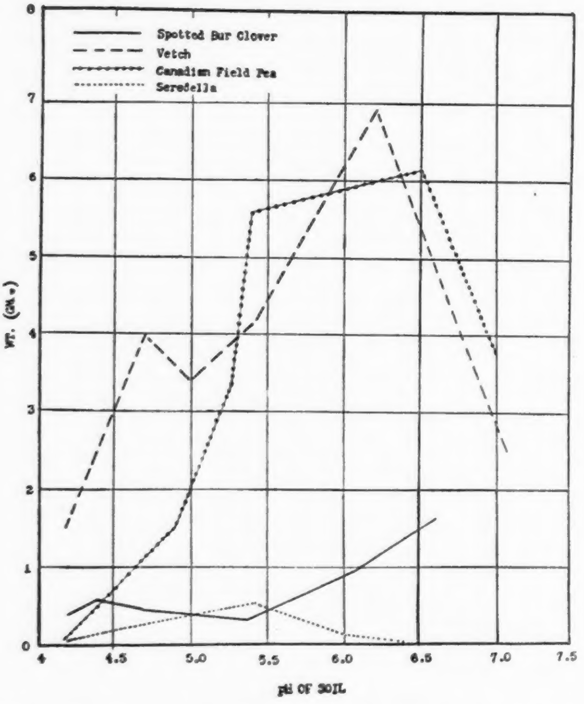

FIG. 5. DRY WEIGHT OF LEGUME PLANTS GROWN ON CLARKSVILLE SIDT LOAN, THE pH OF WHICH WAS ARTIFICIALLY MODIFIED

clover grew as well at a decidedly higher H-ion concentration than the legumes previously named. It appears also that varietal differences with reference to acid tolerance exist within the same species of plants. Thus although sweet clover grows best at a pH of about 6.5 to 7.0 the Hubam sweet clover seems to have a wider range of acid tolerance and may make a fair growth at a pH of 5.

Plate 3 shows clearly the difference in growth response with respect to the H-ion concentration of various legumes. It will be noted that the bur clover and Austrian field pea made very good growth at a pH of 4.5, whereas the sweet clover required a soil with a pH of 7.0 for its best growth.

DISCUSSION

Coville (6) stated that the cowpea, hairy vetch, crimson clover, soybean, lupine, and seredella are useful on acid soil types. Popular agricultural opinion also conveys the idea that the above named legumes are to a considerable degree acid tolerant and therefore particularly adapted to many of the acid soil regions of the south. The question arizes, is this assumption correct? If so, what is the relationship of these varieties on the basis of a comparative acidity test? Furthermore has the soil reaction an effect on the plant or on the nitrogen assimilating bacteria or both? A good many investigators (5, 6, 11, 12, 21, 22, 23, 24) have shown that there are differences in the capacity of the plants to grow on acid soils. Other workers (8, 9) have found that there are differences in the nitrogen assimilating bacteria with respect to their ability to grow in an acid or alkaline medium. MacIntire (16) believes that the harmful effect of soil acidity is not on the plant but that it may effect the nitrogen assimilating bacteria. Truog (25) has shown that the harmful effect of an acid soil is due to the lack of calcium available to the plant. Bryan (3) further found that the greater the acidity of the nutrient solution the less power the plant has of obtaining its calcium for growth processes. Other workers (10, 17, 18) have shown that substances in solution in an acid soil may be toxic to the plant. The problem, therefore, of soil acidity and the reason for its injurious effects on the plant is a complex one in which many factors operate. The present work is not an attempt to deal with the harmful effects of an acid medium on the plant but a comparative study of some southern legumes with relation to their tolerance to soil acidity.

It was noted previously that the mono- and di-potassium phosphates in the nutrient solution of series I were not sufficient buffer to maintain a constant H-ion concentration. Even when 300 cc. of nutrient solution was added to the jars daily the pH of the solution was not maintained. This was no doubt because of the large amount of sand used, together with the fact that the basic substances had not been removed. When this basic material was removed with concentrated HCl as was done for sand used in the second series, it was found that the H ion concentration could be maintained if the culture solutions were applied daily.

By adding potassium acid phthalate, in concentration of .0052 M, the pH values were fairly well maintained. By comparing the green weight of plants from jars which received nitrate and were kept at a pH of 7.0, but which received the buffer solution, with the jar not receiving the buffer, it will be noted that the potassium acid phthalate reduced the green weight of red clover 40.3 per cent and that of vetch 15.6 per cent. On the other hand the green weight of the California bur clover (not inoculated) was increased when the buffer solution was added, whereas the inoculated plants were little affected. These results on the toxicity of the phthalate buffer agree with the findings of Dustiman (7) who found toxicity to the tomato and barley plants when 500 ppm. of potassium acid pthalate was added to the nutrient solution.

The toxicity of the buffer solution to red clover plants was greater when they were grown at a pH of 7.0 than at a higher H ion concentration. This might partially be due to an unbalanced condition of the nutrient solution at a pH of 7.0. It has been shown by Tarr and Noble (23) that about eight-ninths of the calcium and less than one-half of the magnesium precipitated from solutions between the pH values of 3 and 7.59. It appears that in this series, particularly for plants receiving nitrates, the precipitation of much of the calcium in excess of magnesium from the solution at a pH of 7 tended, together with the buffer solution, to bring about greater toxicity than was obtained at a pH of 4.5 and 5.8 when the Ca and Mg concentration were present in a more balanced relation. Such a balanced relation was noted by Loew (14) to be of extreme importance to the permeability of the plant. It is very evident in work pertaining to the H-ion concentration in plant growth that analyses be made (23) of the salts remaining in solution at the various pH values in order to maintain a uniform salt concentration through the series. In the second series of these experiments the precipitation of salts from solution was noted in the lack of sufficient iron in the medium at the neutral point, and consequently the plants became chlorotic. However, the addition of 5 cc. of a 0.1 per cent solution of ferric tartrate tended to bring the plants back to normal color even at a pH of 7.

In making a comparison of the uninoculated red clover and vetch plants, it will be seen that the greatest growth on a green weight basis was obtained at a pH of 5.8. On the other hand the inoculated plants made their greatest growth at a pH of 7.0. This would offer one of two suggestions: first, that the nitrogen assimilating bacteria were retarded in their development at the lower pH value; or second, that the plants were not sufficiently inoculated in their early development. If we note, however, that a greater percentage of inoculation occurred at a pH of 7 than at a lower pH range, it becomes apparent that the first suggestion is in order, namely, that the bacterial growth was retarded at the lower pH value and concomitantly plant growth was also retarded. It will also be seen that the plants receiving nitrates made as good growth at a pH of 5.6 as at 7.0. These results on the growth of the nitrogen-assimilating bacteria are in agreement with Fred's (8) findings on the growth of the alfalfa bacteria in pure culture at varying pH values. The difference in growth response of the velvet bean and vetch plant to varying H-ion concentration may be observed in plates 1 and 2.

The results obtained from a comparative test of legumes grown in sand culture solutions here reported indicate the following gradient of low to high acid tolerance: red clover, vetch, seredella, California bur clover, spotted bur clover, and velvet bean.

The data from the third series of the experiment in which the soil reaction was changed by the addition of a 2.3 *N* acid or *N* base are comparative only, since the reaction in the soil could not be kept constant throughout the entire period of plant growth. The reader must also keep in mind that no conclusions

can be given with respect to modifying factors on plant growth, such as aluminum, magnesium, or iron toxicity in the acid range, because these substances are brought into solution. All that can be said is that the pH was determined at the time the seed was planted and again at harvest. Nevertheless, as previously intimated, the results are comparative and, in the mind of the writer, the plant growth was more normal and conclusive than that which could be obtained in sand or water cultures.

The data on the germination of the various legumes, particularly the sweet clover, show that the seed will germinate in very acid soil but that the plant dies soon afterwards. Some of the larger type of seed, such as the Canadian field pea, also germinate readily and may even produce good growth in an acid soil, possibly because of the readily available food in the cotyledons, but sooner or later the plants turn yellow and die. These results are somewhat contrary to those of Joffe (12), who found that alfalfa plants, even at a pH of 3.5, when once established had a normal green color and made good growth. The soil used in the present experiment was very low in total nitrogen. However, had there been a greater supply of available nitrogen, these plants also might have developed at a higher H-ion concentration.

It appears that the plants here tested grew better at a pH of 6 to 6.5 than at a pH of 7.0. The total dry weight of the plants as shown by figure 3 and plate 2 was much reduced at a pH of 7.0. It appears that when $Ca(OH)_2$ was used to change the soil reaction to neutrality the plants did not grow as well as when NaOH was used for this purpose (see table 3 and figures 4 and 5) in spite of the fact that a much better physical condition of the soil obtained with $Ca(OH)_2$. This better growth when NaOH was used to change the soil reaction was particularly noted in the case of the sweet clovers. This seems to be in agreement with the fact that these plants habitually grow well in alkali regions. Results from field tests at this station have also shown that legume plants grown on soils similar to that used by the writer in this experiment do not respond to lime. These results suggest that the soil when made neutral with $Ca(OH)_2$ had such a high lime content that it tended to precipitate the phosphate and that this becomes the limiting factor in plant growth, and therefore only legumes with a high lime requirement (26) would be expected to respond to this treatment.

Breaux (2) noted that when lime was added to acid soils, the neutrality was not long maintained but that a change occurred in pH within 24 hours. He noted that after a period of three months the pH had changed over a range of 0.5 to 1.5 units below the initial value produced by liming. In the present experiment the pH from the beginning to the time the experiment terminated varied from 0 to 0.5, depending on the H-ion concentration of the soil at the time the experiment was started. When the pH of the soil was artificially altered from the normal of 5.9 to that of 7.0 or 7.5 then during the period of the experiment a change of 0.5 pH was noted, but when the normal pH of the soil was not changed over 0.5 to 1.0 very little change in pH occurred during the

period of the experiment, though fluctuations may have occurred during the term of the experiment. Bauer (1) noted variations in the H-ion concentration of soils with different moisture contents and he suggested that these periodic pH fluctuations should be considered in soil acidity studies. Such periodic measurements were not made in this experiment, but the extent of such changes from time to time would depend upon the buffer capacity of the soil.

A study of figures 4 and 5 will show that there is a marked variation in the capacity of the various legumes to grow on acid soils. Seredella and subterranean clover were particularly able to make good growth in a relatively acid medium whereas the sweet clovers grew better in a more neutral soil. The range of acid tolerance for this last series in which the pH of the soil was modified from high to low acidity is as follows: seredella, subterranean clover, vetch, bur clover, Austrian field pea, soybean, Canadian field pea, crimson clover, Hubam clover, and biennial white sweet clover.

In experiments concerned with symbiotic forms, such as are reported here, one questions how the host can adapt itself to a relatively acid soil when the bacterial organism prefers a neutral medium. To this effect Fred (9) has shown that some forms of the nitrogen assimilating bacteria, as the lupine form, are able to make good growth at as low a pH as 3.2 whereas such forms as alfalfa bacteria can develop at a pH no higher than 4.9. Thus it may be partially for this reason that the seredella plant, for instance, can make better growth in acid soil than some of the other forms of legumes here used. However, it appears that if the soil is well supplied with nitrogen, many of the legumes here tested can make considerable growth in a comparatively acid soil.

SUMMARY

The present investigation is a comparative acid tolerance test of southern legumes. The legumes were grown in a modified form of Tarr and Noble's basal culture solution with and without potassium acid phthalate; modified form of Crone's solution; and Clarksville silt loam soil, the pH of which was changed by addition of an acid base.

1. It was found that, when 10 kgm. of pure silica sand was used, it was impossible to maintain a constant pH, even if the culture solution was added daily in large amounts. Potassium acid pthalate used at 0.0052M strength during the first half of the experiment and one-half that amount during the last half of the test, tended to keep the pH constant if the nutrient solutions were added daily or every 48 hours.

2. Toxicity of potassium acid pthalate was noted in the case of red clover and vetch whereas it actually stimulated the growth of California bur clover.

3. When 1 kgm. of pure Ottowa silica sand was used, which had been treated with concentrated hydrogen chloride and washed free of acid, the pH could be maintained constant provided about 200 cc. of Crone's solution was applied daily. The pH of the solutions used was altered with normal hydrogen chloride and sodium hydroxide.

4. The results of the comparative legumes tests on sand cultures show the following gradient of tolerance of low to high acidity; red clover, vetch, seredella, California bur clover, spotted bur clover, and velvet bean.

5. Results from the first series of the experiment tend to show that the vetch and bur clover plants can grow on a decidedly acid solution, provided nitrates are present. If, however, nitrates are not present but when the plants were inoculated such good growth in an acid range was not noted.

6. When the pH of soil was changed by the addition of an acid or base, the hydrogen ion was approximately maintained over a period of six and eight weeks provided the soil had first come to an equilibrium.

7. The best growth of most legumes was produced at a soil reaction of pH 6.0–6.8. When sodium hydroxide was used to change the reaction it destroyed the physical properties of the soil but some plants, particularly sweet clover, seemed to grow better when sodium hydroxide was used to change the reaction than when calcium hydroxide was used under similar hydrogen ion concentrations. This was particularly true when the soil was brought to a pH of 7.2 and 7.4.

8. The following range of acid tolerance was noted among legumes when grown on soil, ranging from high to low acidity: seredella, subterranean clover, vetch, bur clover, Austrian field pea, soybean, Canadian field pea, crimson clover, Hubam clover, and biennial white sweet clover.

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PLATE 1

VETCH PLANTS GROWN IN SAND CULTURE SOLUTIONS MAINTAINED AT DIFFERENT pH VALUES

FIG. 1. Inoculated, received a minus nitrogen culture solution. Solutions 25 = pH 4.5, 23 = pH 5.8, 27 = pH 7.0.

FIG. 2. Uninoculated, received a plus nitrogen culture solution. Solutions 22 = pH 4.5, 24 = pH 5.8, 28 = pH 7.0.

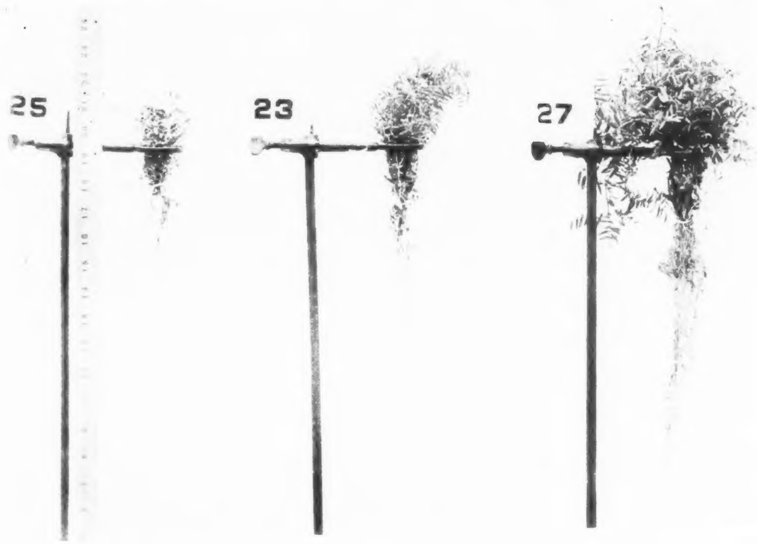

Fig. 1

Fig. 2

PLATE 2

LEGUME PLANTS GROWN IN SAND CULTURES MAINTAINED AT THE pH INDICATED. INOCULATED PLANTS RECEIVED THE NITROGEN IN THE CULTURE SOLUTION

FIG. 1. Velvet bean.
FIG. 2. Seredella.


4.5
4.5
5.8
5.8
7.0
7.0
Uninoc.
Inoc.

Fig. 1


4.5
Inoc.
4.5
Uninoc.
5.8
5.8
7.0
7.0
Uninoc.

Fig. 2

PLATE 3

LEGUMES GROWN ON SOIL, THE H-ION CONCENTRATION OF WHICH WAS ADJUSTED AS INDICATED

FIG. 1. Canadian pea.
FIG. 2. Austrian pea.
FIG. 3. Biennial white sweet clover.
FIG. 4. Spotted bur clover. Note *L* indicates $Ca(OH)_2$ used to change soil reaction.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

AUTHOR INDEX

SUBJECT INDEX

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O[illegible]	
Total crops	2.[illegible]
Alfalfa (8 tons)	5[illegible]
Peas (4 tons)	13.6
Sugar beets (20 tons)	[illegible]3.0
Potatoes (300 bu.)	5.0